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ALTERNATIVE ENERGY SOURCES FOR  
UNITED STATES AIR FORCE INSTALLATIONS

Michael D. DeWitte

Air Force Weapons Laboratory  
Kirtland Air Force Base, New Mexico

August 1975

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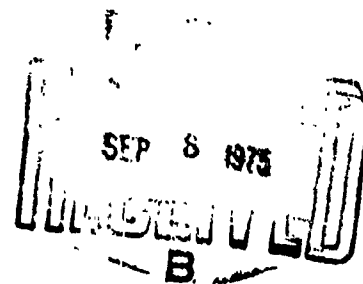
## ALTERNATIVE ENERGY SOURCES FOR UNITED STATES AIR FORCE INSTALLATIONS

Michael D. DeWitte, Captain, USAF

August 1975

Final Report for Period July 1974 - June 1975

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AIR FORCE WEAPONS LABORATORY  
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Kirtland Air Force Base, NM 87117

This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico under Job Order 21022E04. Captain Michael D. DeWitte (OL-AA, AFCEC/DEZ) was the Laboratory Project Officer-in-Charge.

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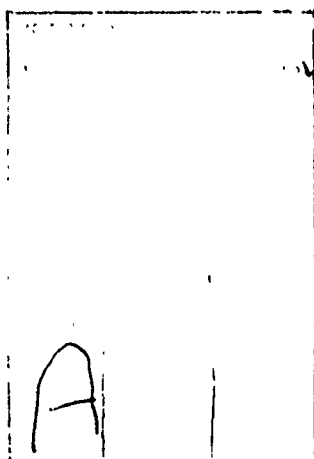
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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) <p>The increasing cost of fossil fuels and corresponding increase in the price of purchased electricity and natural gas have indeed made an impact on the Air Force. This report is concerned with the consumption and cost of facilities-related energy, both present and future, at Air Force installations, and it presents a basic assessment of the potential of alternative energy sources. In particular-solar, wind, and geothermal energy resources are investigated. Solar energy applications include space heating and cooling, which received the (OVER)</p>		

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ABSTRACT (Cont'd)

most emphasis because of recent work at the Air Force Weapons Laboratory (AFWL), as well as solar thermal conversion and photovoltaic systems. Representative installations were chosen for heating and cooling studies; whereas, solar thermal and photovoltaics received only a general investigation. Wind energy potential is discussed and analysis accomplished for selected conus bases and major Alaskan sites. Geothermal energy resources are reviewed briefly and potential user installations presented. This effort was accomplished in support of the AFWL Energy R&D program and under direction of the Air Force Energy R&D Steering Group. Only fixed installations have been addressed as a result of the present state-of-the-art of energy conversion systems, as well as their capital intensive nature which rules out diverse mobility or BARE BASE applications

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PREFACE

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## SECTION I

## INTRODUCTION

## 1. ENERGY CRISIS OVERVIEW

The three major energy sources available at present are fossil fuels, nuclear energy, and solar energy. The other primary sources which are continuous and localized are geothermal and tidal. Man has been very fortunate in that the world's reserves of fossil fuels have been sufficient to enable him to embark on the road of progress. The successful manipulation of energy has been an essential component of man's ability to survive and develop socially. The use of energy has been essential in the supply of food, physical comfort, and in improving the quality of life beyond the basic activities necessary for survival. There are two factors which control the utilization of energy: (1) available resources and (2) the technology to convert the resources to useful heat and work (ref. 1).

The steam engine was the first mechanical prime mover to provide basic mobility, but it did not become important until after 1700. From 1700 on, the power output of energy-conversion devices increased by roughly 10,000 times, with most of the growth occurring in the past century. This technology and the innovations which parallel it have created the exponential increase in energy consumption. Figure 1 shows both history and projection of energy consumption in the United States.

Additional projections indicate that by the year 2200, approximately 30 percent of the total power requirements will have to be met by energy sources other than those available today.

Let us now look at a few basic facts of the energy picture (ref. 2)

- a. Current projections of the total U.S. energy demand show a growth from approximately  $70 \times 10^{15}$  BTU in 1972 to nearly  $300 \times 10^{15}$  BTU in the year 2020.
- b. During the next 30 years, the U.S. will consume more energy than it has in its entire history.
- c. The obtaining, refining, distributing, and consuming of fuels account directly for 10 percent of the nation's economic activity, or \$125 billion per year.



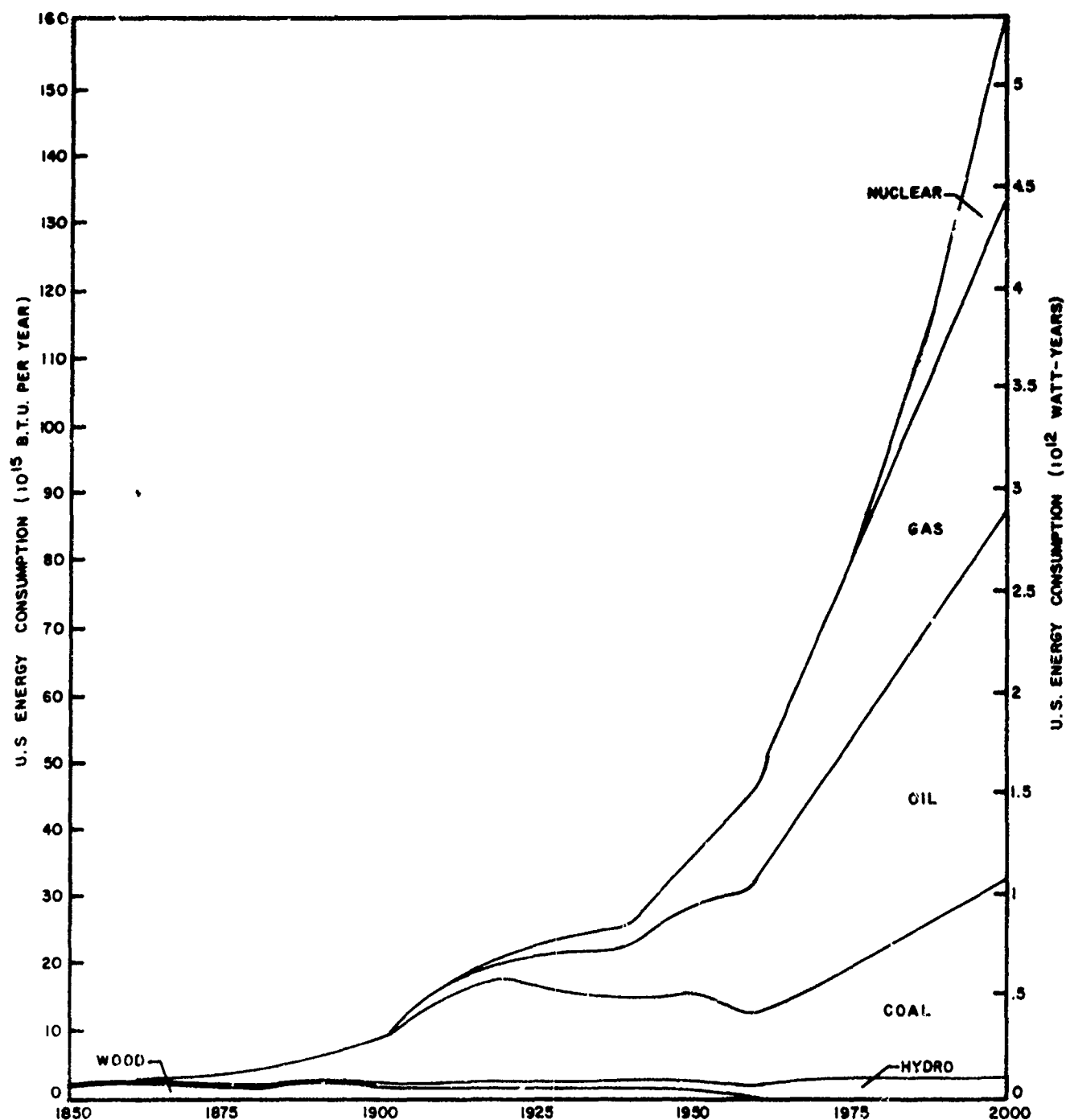


Figure 1. The U.S. Energy Consumption (ref. 1). The U.S. energy consumption has multiplied some 30 times since 1850, when wood supplied more than 90 percent of all the energy units. By 1900 coal had become the dominant fuel, accounting for more than 70 percent of the total. Fifty years later coal's share had dropped to 36.5 percent and the contribution from oil and natural gas had climbed to 55.5 percent. In 1970 coal accounted for 20.1 percent of all energy consumed, oil and gas 75.8 percent, hydropower 3.8 percent and nuclear energy 0.3 percent.

- d. The U.S. demand for oil is increasing by 7 percent each year.
- e. Domestic production of natural gas and crude oil reached an all time high in 1972 and has been decreasing ever since.
- f. The petroleum industry is short of domestic refining capacity by about 3 million barrels per day.
- g. Estimates show that to achieve hemispheric (not domestic) self-sufficiency by 1980 means closing an energy gap of 9 million barrels per day.
- h. It is estimated that the U.S. will be required to import some 16 million barrels per day of oil from overseas in 1990, of which 14 million will originate from the Middle East or Africa. This is compared to a total estimated demand of 32 million barrels per day. The U.S. domestic wells will be able to supply approximately 6 million barrels per day, with the Alaskan North Slope field possibly supplying an additional 4 million barrels per day.

## 2. ENERGY SOURCE ASSESSMENT

In any assessment of energy supply and demand, the implications of continued economic growth in a closed planetary system will have to be faced. As Jay W. Forrester (ref. 3) states: "It is not a question of whether growth will cease, but rather whether the coming transition to equilibrium will occur traumatically or with some measure of human intervention which may head off some of the most tragic outcomes." One of the most interesting "economic" equilibrium concepts is that proposed by H. T. Odum (ref. 2). He suggests that money is no longer an adequate medium to describe accurately our various resource allocations and human transactions. Dollar appraisals need to be augmented by a system of energy accounting and simulation to describe how underlying energy-matter exchanges operate and how hidden energy subsidies or outflows obscure or prevent accurate accounting of the real costs, benefits, and trade-offs in human activities. It is no longer a matter of pure economics when we consider energy resources. Our finite fossil resources will eventually be exhausted, and using a common phrase associated with the plight of numerous species of the animal kingdom, "extinct is forever." The entire gross national product will not bring back one barrel of crude oil after it has been consumed in quenching the energy thirst. The price of oil can only increase and unless an adequate means of evaluating or describing our resource allocations is developed, serious worldwide economic problems will arise. Mr. Odum's concept must be taken into careful consideration

in all future discussions or analyses of energy sources. This, as well as technical feasibility and environmental and social desirability, has to be established prior to any major program to develop one or more alternative energy sources (ref. 5).

## SECTION II

### ENERGY RESOURCES OF THE EARTH

#### 1. GENERAL

The energy resources of the earth are solar energy (current and stored), the tides, the earth's heat, fission fuels, and possibly fusion fuels.

The primary source of energy is solar radiation, supplemented by small amounts of heat from the earth's interior and of tidal energy from the gravitational systems of the earth, moon, and sun.

The most difficult concept for people to understand is the short time span in which fossil fuels will be exhausted. People today are accustomed to the exponential growth rate in the consumption of fossil fuels, but apparently they do not understand that fossile fuels represent a finite reserve which has a useful life of only a few hundred years. This life span is shown in figure 2 as a "fossil fuel impulse function. (ref. 6). Figure 3 shows this transitory function for world oil production (ref. 1).

What will provide industrial energy in the future on a scale at least as large as the present one? The answer obviously lies in man's growing ability to develop and exploit other sources of energy. Nuclear energy appears to be the short term answer, but eventually, the much larger source of solar energy must be developed. Such resources of energy would no longer limit the growth of industrial activity by the scarcity of energy but rather by the physical and material limitations of a finite earth, together with the principles of ecology (ref. 1).

#### 2. CONTINUOUS ENERGY RESOURCES

Let us now take a look at the flow of energy through the earth's surface environment. The inward flow of energy has three main sources: (1) solar radiation, (2) thermal energy from the earth's interior, and (3) tidal energy.

The solar input to the earth is 1353 watts per square meter (428 BTU/ft<sup>2</sup> hr) or  $1.73 \times 10^{17}$  watts intercepted at the earth's surface. The continual flow of heat from the earth's interior has been found to be approximately 0.063 watt per

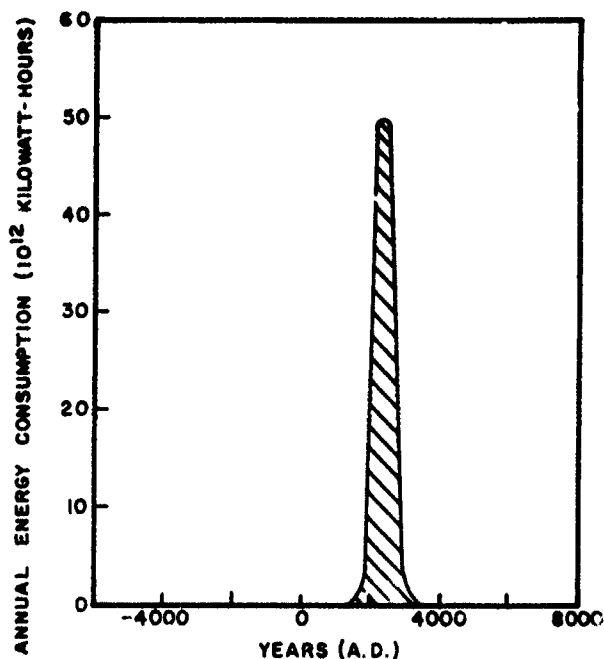


Figure 2. World Consumption of Fossil Fuel--Past, Present, and Future (ref. 6)

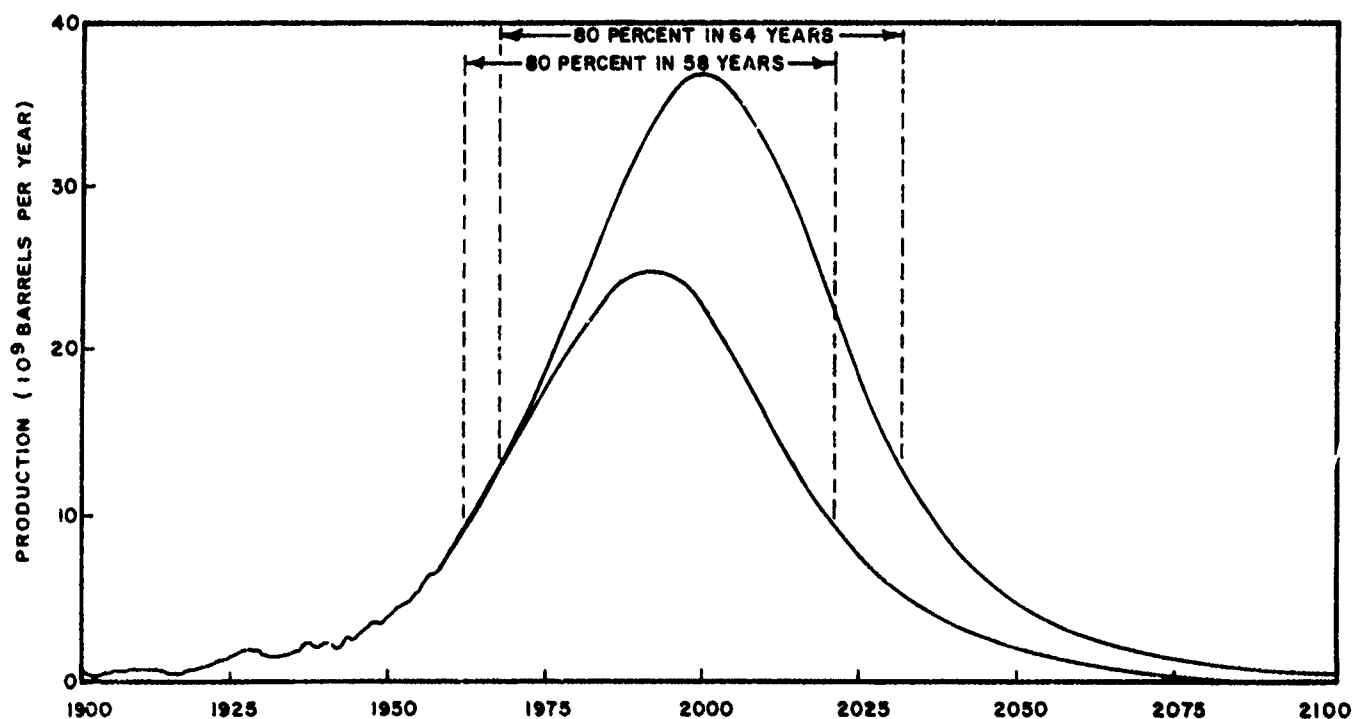


Figure 3. Cycle of World Oil Production (ref. 1). This cycle is plotted on the basis of two estimates of the amount of oil that will ultimately be produced. The upper curve reflects Ryman's estimate of  $2,100 \times 10^9$  barrels and the lower curve represents an estimate of  $1,350 \times 10^9$  barrels.

square meter. For the earth's total surface area, this amounts to  $32 \times 10^{12}$  watts. Therefore the total power influx into the earth's surface is  $1.73035 \times 10^{17}$  watts, of which solar radiation accounts for 99.98 percent.

### 3. FOSSIL FUELS

Industrialization and associated technological advancement have withdrawn our fossil fuel deposits at an ever increasing rate. Take coal, for example; the production and consumption of coal since 1940 is nearly equal to the total cumulative consumption up to that time. Although petroleum and its related products were not utilized in significant amounts prior to 1880, the 80-year period from 1890 through 1970 has shown an average rate of increase of almost 7 percent per year with a doubling period of 10 years. As with coal, the major production period is rather brief with 102 years (1857 to 1959) required to produce the first half of cumulative production, while only 10 years (1959 to 1969) were required for the second half (ref. 1).

The industrial consumption of energy in the world is presently doubling every decade. This rate of growth is real, and it is very obvious that it cannot be maintained for very long when one considers the simple fact that we are exploiting a finite and essentially fixed supply. If one can obtain and subsequently analyze past and projected rates of fuel production and consumption, as well as the initial supply, a reasonable life expectancy of the fuel can be derived.

#### a. Coal

One of the most recent compilations of current information on the world's initial coal resources was made by Paul Averitt of the U.S. Geological Survey (ref. 1). His figures represent minable coal which is defined as 50 percent of the coal actually present. Coal in beds as thin as 14 inches and extending to depths of 4,000 to 6,000 feet are included (see figure 4). Examining Averitt's estimate of 7.64 trillion metric tons as the initial supply and assuming the present production rate of 3 billion metric tons per year doubles no more than three times, we can estimate the peak rate of production will be reached during the period from 2100 to 2150 (ref. 1).

These statistics show that coal may indeed play an important role in providing energy for the world; however, what about the environmental and epidemiological hazards of burning coal? Data have been presented implying that

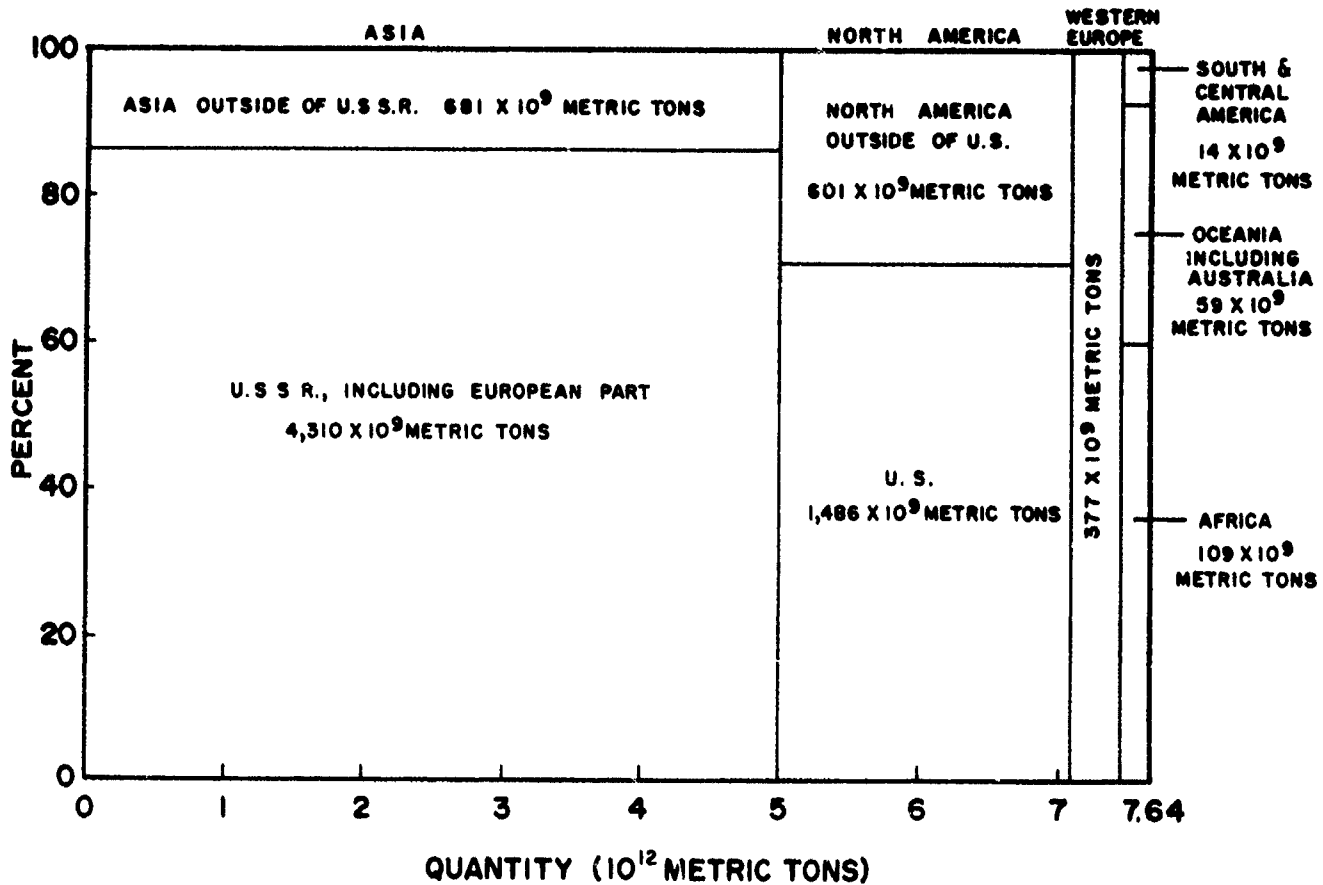


Figure 4. Coal Resources of the World (ref. 1). These resources are indicated on the basis of data compiled by Paul Averitt of the U.S. Geological Survey. The figures represent the total initial resources of minable coal, which is defined as 50 percent of the coal actually present. The horizontal scale gives the total supply in a continent. From the first block, for example, one can ascertain that Asia has some  $5 \times 10^{12}$  metric tons of minable coal, of which about 86 percent is in the U.S.S.R.

the pre-1968 health cost to New Yorkers from unrestricted coal burning was several thousand deaths per year, plus uncounted non-fatal disabilities of varying severity. Social costs also include the 50,000 American coal miners with black lung disease. Now the despoliation of the land by strip mining must be added to the aforementioned social costs. These factors coupled with basic environmental problems have greatly reduced coals contribution to the energy budget. Today, coal provides only 18 percent of the nation's energy compared to 70 percent in 1900 and 36 percent in 1950. If we remind ourselves that the environmental and social difficulties associated with coal extraction and utilization are correctable and are becoming more economical as the price of oil continues to rise, perhaps then we will see coal as well as oil shale and even tar sands in their proper light: raw materials for a synthetic fuel industry. There appears to be enough time between now and say 1985 to develop environmentally acceptable methods for producing oil from coal and/or oil shale at less than \$7 a barrel. In addition, programs now under study will probably lead to the production of clean synthetic natural gas from coal at approximately \$1.20 per 1,000 cubic feet (equivalent to \$7 a barrel for petroleum) (ref. 1).

b. Oil

Estimates of ultimate world production of oil range from 1,350 to 2,100 billion barrels. Using the higher figure and current estimated rates of consumption, the peak in the rate of world production should be reached about the year 2000. The period of consumption of the middle 80 percent will be 58 to 64 years depending on which estimate is used (see figure 3). A significant but finite amount of oil can be extracted from tar sands and oil shales with a total estimated potential of 3,100 billion barrels in shale containing from 10 to 100 gallons per ton as per a world summary of oil shales by Duncan and Swanson of the U.S. Geological Survey. Figure 5 shows the world oil resources and their distribution. Of the 200 billion barrels estimated in the United States, 160 to 170 billion barrels represent the ultimate total discoveries in the coterminous U.S. and the adjacent continental shelves. The total number of well discoveries up to 1965 represent about 82 percent of the estimated total. Only a speculative estimate can be made of the eventual petroleum discoveries in Alaska. The Prudhoe Bay field appears likely by present estimates to contain about 10 billion barrels. One must consider that even 30 billion barrels represent less than a 10-year supply for the United States at its present rate of consumption (ref. 1).



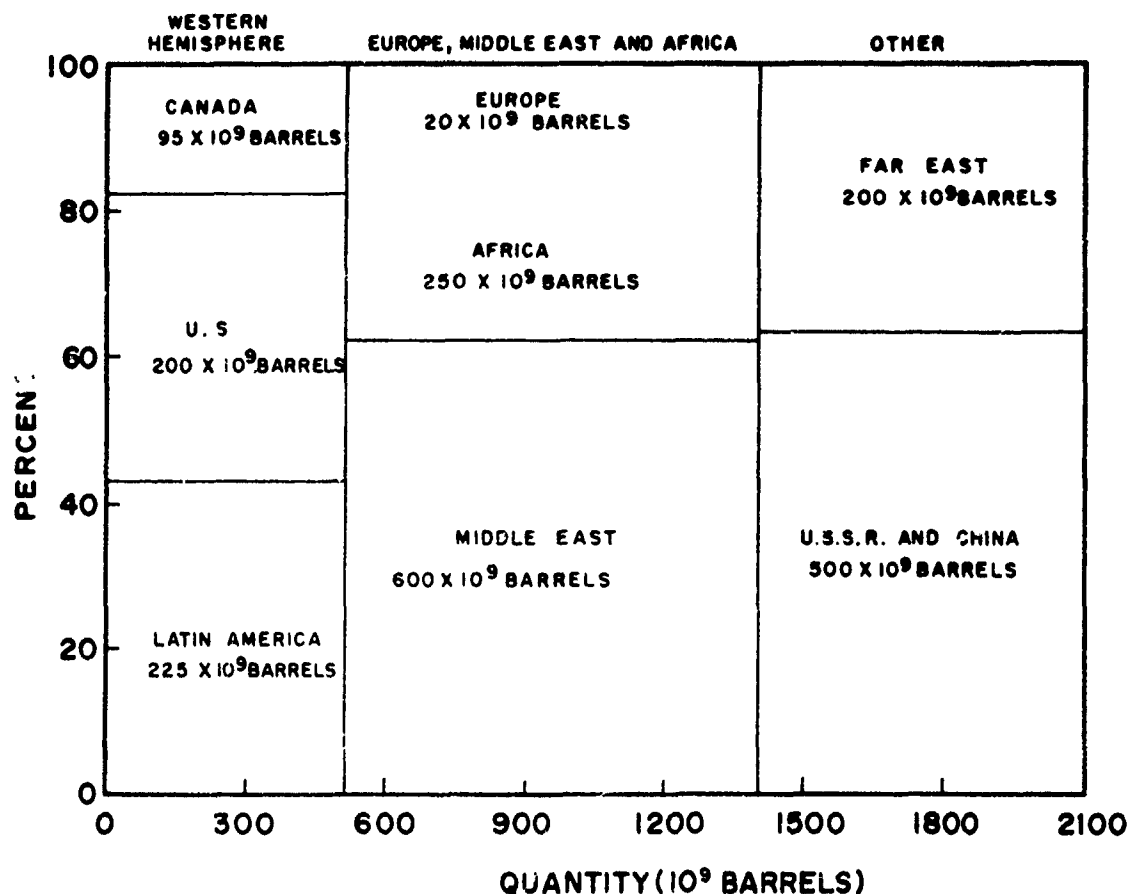


Figure 5. Petroleum Resources of the World (ref. 1). These resources are depicted in an arrangement that can be read in the same way as the diagram of coal supplies in figure 4. The figures for petroleum are derived from estimates made in 1967 by W. P. Fyman of the Standard Oil Company of New Jersey. They represent ultimate crude-oil production including oil from offshore areas, and consist of oil already produced, proved and probable reserves, and future discoveries. Estimates as low as  $1,350 \times 10^9$  barrels have also been made.

## c. Natural Gas

Current annual production of natural gas in the United States is approximately 22.5 trillion cubic feet. The Bureau of Natural Gas (BNG) estimates that production will fall to as low as 7.3 trillion cubic feet or as high as 17.4 trillion cubic feet by 1985. Either figure represents a gloomy picture and well below demand. The general conclusion of a recent BNG report is that the United States reached peak domestic natural gas production in 1972 rather than the projected 1975-1980 date and will continue to decline indefinitely. The ultimate amount of natural gas in the continental United States has normally been estimated at about 1,075 to 1,450 trillion cubic feet, but BNG now believes that the best approximation is closer to that of M.K. Hubbert of the U.S. Geological Survey with an estimate of 500 trillion cubic feet. Figure 6 illustrates the problem forecasted by the gas industry for the supply and demand of natural gas through the year 1990 (ref. 7). The figure clearly shows that even with the gasification of coal, gas imports from Canada, liquefied natural gas (LNG) imports, and the potential supply of gas from the north shore of Alaska, there will still be a substantial deficit in the supply of natural gas compared to the demand estimated by 1990. Simple economics dictate that an escalation in natural gas prices will follow the supply to demand deficit. Table 1 shows projected energy costs of natural gas and electricity through 1990, and forecasts an approximate 300 percent increase over the price of natural gas in 1973 (ref. 8). It must be pointed out that figure 6 and table 1 are considered very conservative at this time (ref. 1).

Fossil fuels, in spite of their drawbacks will be needed for many years. Coal, along with the oil shale of western Colorado, is a unique U.S. reserve of fossil fuels. Coal provides only 18 percent of the nation's energy needs, and this has steadily decreased with time as indicated by coal supplying 70 percent of the energy in 1900 and 56 percent in 1950. The major reason the utilization and technology of coal is currently languishing is attributable to the sociological, environmental, and epidemiological aspects of the present modes of coal extraction and use. Oil shale may present an even more severe environmental problem, but public demand can and should force corrections of such difficulties. As previously discussed, perhaps coal and oil shale now appear in their proper perspective--as raw materials for a synthetic-fuel industry that can limit economic and political threats from abroad.

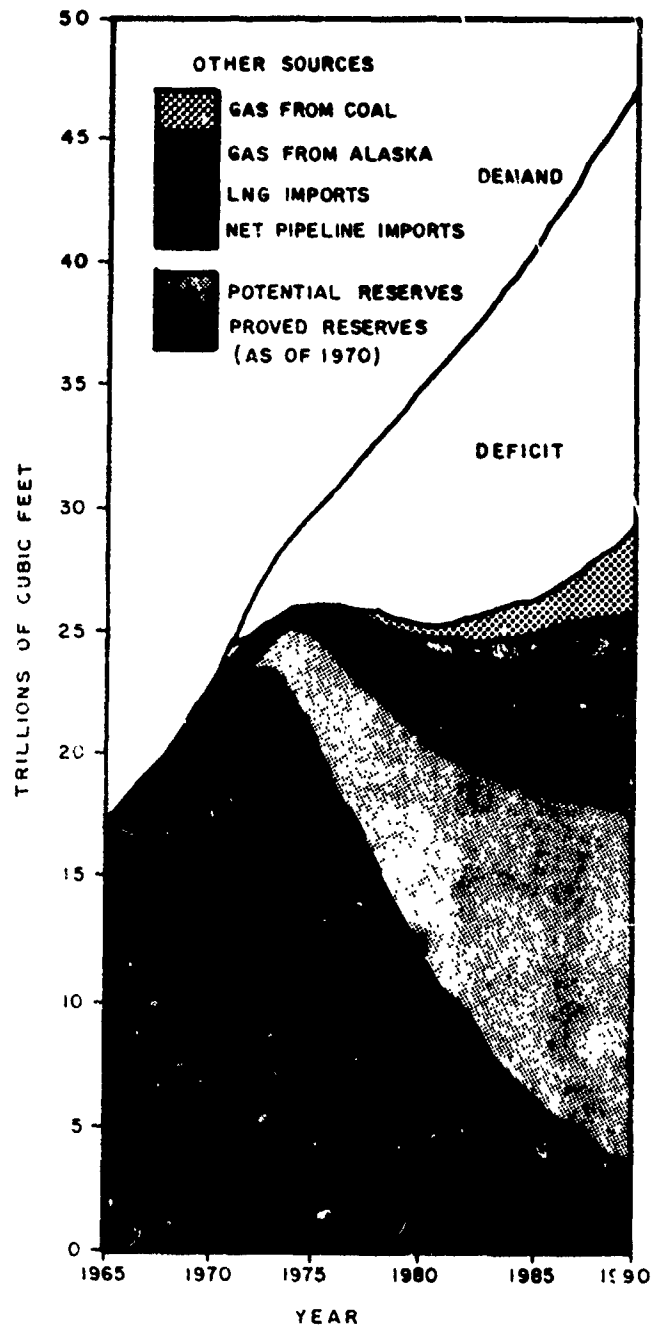


Figure 6. Natural Gas Demand Versus Supply (ref. 7)

Table 1

PROJECTED PERCENTAGE INCREASES IN NATURAL GAS AND  
ELECTRICITY BY GEOGRAPHIC AREA (1972 BASE) (REF. 8)

Area*	1980 Percent	1985 Percent
	<u>Natural Gas</u>	
East	182	254
South East	212	313
East Central	202	300
South Central	252	387
West Central	205	299
West	227	341
	<u>Electricity</u>	
East	143	161
South East	172	197
East Central	140	161
South Central	179	220
West Central	141	172
West	150	175

\*See figure 7.

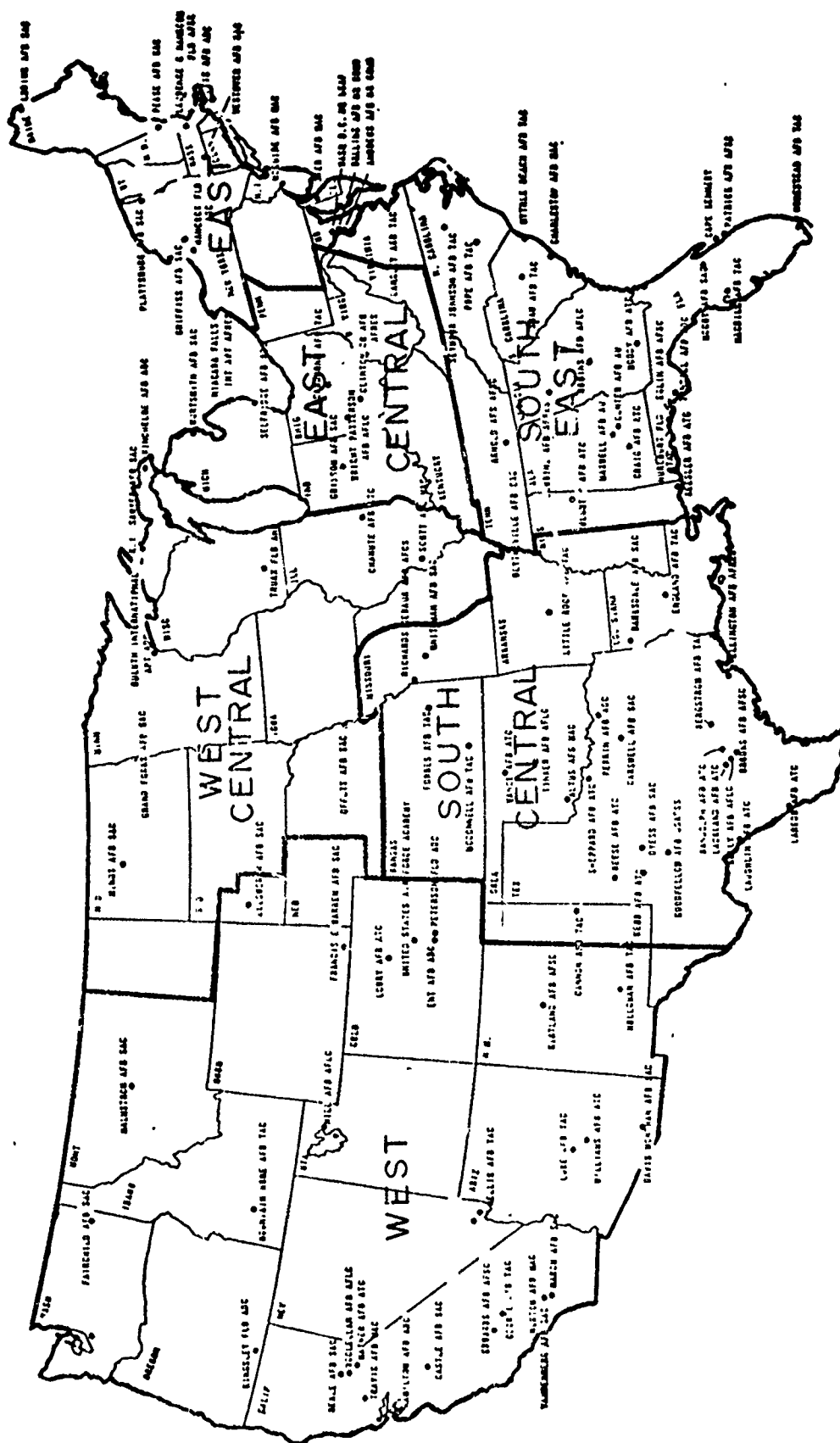


Figure 7. Power Regions Used in Analysis (ref. 8).

Within the next 10 years there seems to be enough time to develop environmentally acceptable methods for producing oil from coal, and maybe from oil shale as well at a competitive price. Other programs now undergoing study will eventually lead to clean synthetic natural gas from coal at reasonable prices. The establishment of a synthetic fuel industry will not be cheap, and to build the capacity required to produce 5 million barrels per day would cost an estimated \$40 billion. The synthetic fuel industry is not completely new, but such a large scale program would be a pioneer development. For example, in Germany, synthetic fuel was used to operate motor vehicles during the latter portion of World War II, and in 1944 the United States initiated a synthetic liquid fuel development program, which continued through 1955. During the 1960's, a \$20 million "Project Gasoline" plant in Aesap, West Virginia, was operated by the Consolidation Coal Company. Today, South Africa obtains 80 percent of its energy from synthetic fuel derived from the coal. The reason the synthetic fuel industry was not continued in the United States is due to economic and political factors as well as the interesting fact that the oil companies have controlling interests in a number of coal firms. A large U.S. synthetic fuel industry might provide a bargaining tool or even a deterrent against the high prices of the Organization of Petroleum Exporting Countries, but then the United States represents only a fraction of the world market. All of the impacts of a synthetic fuel industry cannot be evaluated realistically at this time (ref. 2).

## SECTION III

## AIR FORCE ENERGY CONSUMPTION\*

The worldwide facilities-related energy consumption by the Air Force and its costs are as follows:

Year	Consumption (MBTU x 10 )	Cost (\$million)
1973	275.8	163.0
1974	248.1	184.7
1975 (est)	(235.2)	(291.9)

The costs may not seem great when compared to the total Air Force budget, but concern must be directed toward future costs and most important the present and future consumption of the rapidly decreasing fossil fuels. First of all a listing of the major energy consumers in the Air Force should be made (Only Alaska and CONUS installations will be included in this study due to available data limitations.) Those USAF installations having a total energy consumption greater than 2,000,000 MBTU are shown in table 2. These 21 installations represent 26 percent of the total Air Force energy consumption in 1974. The major consumers of electricity, natural gas, fuel oil, and coal are as follows:

Base	MWH
<u>Electricity</u>	
Arnold Engineering Center	592,609
Wright-Patterson	277,500
Eglin	226,437
McClellan	187,500
Tinker	187,500
Kirtland	175,237
Mountain Home	165,260
Kelly	162,000
Robins	161,700
Keesler	159,717

\*NOTE: For the purposes of this report, energy consumption relates only to facilities-related energy, i.e., space conditioning and electrical power production.

Base	MBTU
<u>Natural Gas</u>	
Elmendorf	3,301,445
Tinker	2,334,500
Kirtland	1,991,216
Hill	1,825,900
USAF	1,241,119
Minot	1,151,600
Kelly	1,103,200
McClellan	975,600
Robins	951,500
Malmstrom	936,000
<u>Coal</u>	
Eielson	3,402,081
Wright-Patterson	2,832,400
Chanute	1,051,282
Rickenbacker	919,300
Kincheloe	457,100
Grissom	340,000
Mt Home	328,147
Griffiss	297,300
Loring	226,100
KI Sawyer	162,800
Kingsley	87,961
Lowry	18,225
<u>Fuel Oil</u>	
Griffiss	1,059,000
Andrews	1,039,500
Plattsburgh	972,000
Loring	970,000
Grand Forks	853,000
Dover	677,131
Scott	662,137
KI Sawyer	659,200
Shemya AFS	564,220
Langley	549,970



Table 2  
 FY 1974 LARGEST AIR FORCE ENERGY USERS (MBTU)  
 (Conversion to electricity estimated at 33 percent)

Base	Total (MBTU)	Electric		Gas (MBTU)	Fuel Oil	Coal	Purch Steam
		MWH	MBTU				
Arnold Engineering Center	6,922,877	592,609	6,065,943	843,472	13,462	---	---
Wright-Patterson	6,097,090	277,500	2,840,490	344,600	79,600	2,832,400	---
Tinker	4,259,250	187,500	1,919,250	2,334,500	5,500	---	---
Kirtland	3,816,502	175,237	1,793,721	1,991,216	31,565	---	---
Elmendorf	3,578,220	1,194	12,222	3,301,445	60,120	---	204,433
Eielson'	3,463,879	400	4,503	---	57,295	3,402,081	---
Hill	3,174,196	112,700	1,153,596	1,825,900	193,500	1,200	---
McClellan	2,901,350	187,500	1,919,250	975,600	6,500	---	---
Eglin	2,897,238	226,437	2,317,809	557,333	26,096	---	---
Robins	2,784,860	161,700	1,655,160	951,500	178,200	---	---
Kelly	2,761,432	162,000	1,658,232	1,103,200	---	---	---
Keesler	2,543,320	159,717	1,634,862	908,458	---	---	---
Minot	2,414,458	119,700	1,225,248	1,151,600	37,600	---	---
Grand Forks	2,386,351	149,800	1,533,351	---	853,000	---	---
Vandenburg	2,255,104	139,000	1,422,804	775,000	57,300	---	---
Lackland	2,237,643	127,033	1,300,311	930,848	6,484	---	---
Mountain Home	2,226,331	165,262	1,691,622	54,110	152,452	328,147	---
Andrews	2,225,524	107,300	1,098,324	87,700	1,039,500	---	---
Chanute	2,099,705	62,791	642,729	286,478	119,218	1,059,000	---
USAF	2,091,627	83,974	859,560	1,241,119	17,948	---	---
Griffiss	2,072,965	57,900	592,665	124,000	1,059,000	297,300	---

The United States energy consumption data, patterns, and projected costs of natural gas and electricity have been examined; now, application of these statistics to a few USAF installations must be accomplished. For example, if the electricity rates increase only one mill (0.1 cent) per kilowatt-hour, the largest 10 Air Force users would experience a total cost hike of \$2.3 million based on 1974 electrical energy consumption.

Upon examining a good cross section of installations and applying the projected energy cost increases as per table 1, table 3 is obtained.

Pure costs show one view of the picture but let us take a step farther and look at the effect on the Base Civil Engineer's total operating budget. This means that we are looking at the total funds required for maintenance, repair, minor construction, supplies, custodial services, equipment, and purchased utilities necessary to operate and maintain the installation (military and civilian pay will be excluded). For example, Tyndall AFB, Florida, has a FY 75 Operating Budget of about \$3.3 million, assuming approval of an additional \$239,000 requested to fund electrical rate hikes. Of the total it is estimated that approximately 48 percent will be spent on purchased utilities. Utilizing the projected electricity and gas costs for 1980, and assuming the total budget will increase by 20 percent during the next 5 years, Tyndall can expect to pay 70 percent of the Base Civil Engineer's operating budget on utilities. Kirtland Air Force Base, New Mexico has an FY 75 budget of \$4.7 million, excluding civilian and military pay, and can expect to pay \$2.4 million for electricity, natural gas, and steam. Using the same assumption as with Tyndall, Kirtland may require 69 percent of their budget in 1980 to pay their estimated utility bills of \$3.7 million.

It should seem rather obvious that the Air Force is indeed experiencing an energy and power crisis. The austere Air Force budget, coupled with increasing costs for fuel and utilities, creates a serious if not detrimental effect on the capability to accomplish a vast and ever-changing mission. It has been proven down through history that the success of military forces is strongly coupled to their ability to command energy in quantities and at such times and places as required by the mission at hand. Alternative energy sources must be developed and utilized. Facilities-related energy research and development must focus on providing space conditioning and electrical power production as well as for mobility/emergency requirements and applications.

Table 3  
PROJECTED ELECTRICITY AND NATURAL GAS COSTS IN FY 1980

Base	Electricity			Natural Gas	
	Unit Cost (\$/MWH)	Total Projected Cost* (\$million)	1980	Unit Cost (\$/MBTU)	Total Projected Cost* (\$million)
	1974			1974	1980
Charleston	22	33 to 38	2.3	0.98	2.07
Hanscom	34	48 to 51	2.4	1.26	2.45
Kincheloe	10	14 to 15	0.5	0.83	1.72
Kirtland	12	18	3.2	0.33	0.72
Luke	22	32	2.0	0.89	1.94
Minot	13	19 to 20	2.3	0.55	1.15
Sheppard	10	15 to 18	1.6	0.66	1.54

\*1974 consumption utilized to compute cost

## SECTION IV

### SOLAR ENERGY

#### 1. GENERAL

Of the various energy sources, whether nonrenewable, such as fossil or some nuclear fuels, or continuous, such as tidal or geothermal, none possesses a greater potential than solar energy.

Prior to 1972 there was little Federal or commercial support in the solar energy field with the exception of solar powered artificial satellites. Programs in Australia, France, Israel, and the Soviet Union were substantially exceeding U.S. effort. The 1972-1973 energy crisis provided the impetus the program needed. The National Science Foundation (NSF) and now the Energy Research and Development Agency (ERDA) have proposed fairly large scale programs and industry has met the challenge with their own internal R&D. A NSF/NASA panel has stated that a substantial development program can technically and economically achieve the following objectives by the year 2020--solar energy to provide (1) 35 percent of the total building heating and cooling load, (2) 30 percent of the nation's gaseous fuels, (3) 10 percent of the liquid fuels, and (4) 20 percent of the electrical energy requirements.

In considering where we are today in the development of solar energy, let us first examine the successful and established applications of solar energy. First of all is the solar evaporation process for the recovery of salts from brines. The world's estimated annual solar salt production is in the neighborhood of 10 million tons per year.

Domestic water heating is another successful and accepted application and is used in perhaps a dozen countries. Israel has an active market for solar water heaters, which they export to Portugal and Brazil. The Japanese have produced and marketed in excess of 1 million solar water heaters. Australia, Peru, the USSR, and southern Florida also produce solar water heaters. It is estimated that nearly 10 million people utilize solar heated water (ref. 9).

Photovoltaic conversion has been a mainstay in space power systems; however, terrestrial activities have been limited. Japan uses photovoltaic conversion in microwave relay stations and unattended navigational lighthouses.

The solar distillation of salt water is in the pilot plant stage with community scale plants in operation or under construction in Greece, Spain, and Australia.

Solar energy applications, such as space heating, cooling, refrigeration, power production, and certain high temperature processes, have not been commercially successful, primarily because of the excessive cost of equipment and installation.

The principal factor limiting the adoption of both solar heating and cooling in the U.S. is the lack of well-engineered and economically manufactured and distributed solar collectors. Development, optimization, production design, and manufacture of these units is the key problem. Additional support is needed for engineering development and design studies, testing and improving systems, optimization studies, cost analyses, and production engineering design, followed by full demonstration and trial public use (ref. 9).

Other solar energy applications to be researched and developed include electrical power generation through the photovoltaic effect or thermal conversion. Solar generation of electricity has unlimited applications, and when technical feasibility and economic viability are ascertained, it will greatly assist in fuel conservation and environmental protection. Far range programs include the Satellite Solar Power Station (SSPS) which would collect solar energy nearly 24 hours per day in its synchronous orbit. Electricity produced from its solar cells would then be fed to microwave generators arranged to form an antenna which would direct a microwave beam to a receiving antenna on earth where the microwave energy is converted back to electricity. Again, this is long range planning, but it re-emphasizes how important solar energy is today and possibly more so tomorrow when conventional fuels are exhausted. Solar energy is the only free and inexhaustible energy resource (ref. 10).

Solar energy conversion technologies are presently in an expanding phase of research and development; hence these are not presently contributing significantly to the Nation's energy supply. It is therefore desirable to describe the current state-of-the-art of these techniques to provide an insight to where solar energy is and where it will go.

## 2. HEATING AND COOLING OF BUILDINGS

The technology of solar heating and cooling of buildings consists of solar supplied space heating, space cooling through heat driven refrigeration cycles,

and domestic hot water heating. These systems function by converting the solar energy incident on a collector surface to thermal energy in a working fluid. The two most common heat transfer fluids are water and air. This working fluid then transfers the heat energy either directly to the conditioned space, to thermal energy storage equipment, to heat driven refrigeration equipment, or it is used directly in the form of domestic hot water. The basic components are the collector, storage unit, absorption or mechanical refrigeration system, a load (facility to be heated and/or cooled), and controls (ref. 11).

#### a. Collectors

The solar collector is the essential item of equipment which transforms solar radiant energy to some other useful energy form. There are three basic categories of collectors: flat plate, concentrating, and photovoltaic--other collectors such as the evacuated glass tube containing tubular elements, combinations of flat plate and photovoltaic, collectors utilizing black fluids in glass or plastic tubes, and honeycomb type collectors are under development, but these are merely variations of the basic collector types.

Only flat plate collectors will be addressed for heating and cooling applications in the following discussion. A flat plate collector utilizes both direct (beam) and diffuse radiation. (Diffuse radiation originates from scattering centers, such as dust and aerosols in the atmosphere.) Concentrating collectors can channel only that direct radiation which makes a particular predetermined angle of incidence with the concentrator frame. It is therefore necessary that concentrating collectors be capable of tracking the sun within about one degree of angle. The design and application of this type of a system are presently too complex to provide high reliability and low maintenance at low cost. Although their higher temperature output improves air-conditioning efficiency, it is not yet economically attractive enough for utilization. Eventually, concentrating collectors will most likely be economical for large buildings which require cooling the year round, but at present, flat plate collectors are the most practical. The basic flat plate collector consists of (ref. 12): (1) Transparent glazing surfaces of glass or plastic to reduce upward heat loss from reradiation, convection, and conduction; (2) An absorber, heat exchanger surface may have bonded or imbedded tubes for heat exchange with water, or it may have fins, plates, or be a porous mat for heat exchange with air; (3) Insulation to

reduce back and side losses; and (4) A containing structure which may be part of the structure of the building. The basic operation consists of heat being captured when solar radiation penetrates the collector's transparent cover and strikes the blackened absorber plate. The thermal energy in the heated plate is then transferred to a working fluid and is circulated to another part of the system where the heat may be stored or used. The heat is then applied to the desired purpose--space heating, cooling, domestic water heating, various industrial type processes or whatever.

#### (1) Cover Plate Materials

The most common cover material is glass; however, significant developments have been made in the field of plastics. In general, for covers to be most effective in trapping thermal energy, they must be opaque to long wave radiation--that is, their absorptance and emissivity must be unity. Glass, in its various compositions, has properties that have long been used to an advantage in solar collectors. Low iron content glass with a refractive index of 1.52 has an average transmissivity of 0.90 for solar radiation at normal incidence. It is also possible to increase this average transmissivity to 0.95 through the addition of films with a refractive index intermediate between glass and air; however, this process is rather expensive at present. The main advantages of glass are its long life if properly supported and protected from shock, and its low transmissivity for long wave radiation (ref. 13).

Typical plastic films which can be used for cover plates on solar collectors include a fluorocarbon film, Teflon; a polyvinyl-fluoride film, Tedlar; a polyester film, Mylar type W; and a rather new material, Sun-Lite. These materials differ in chemical composition, physical, and radiation characteristics. It must be emphasized that these plastics cannot be simply substituted for glass as a result of their varying properties. Typical properties of these plastics can be generalized as their being used in thin sections; being partially transparent to long wave radiation; depending greatly on temperature in the determination of actual physical properties; and having a life expectancy that is limited by wind flexing, elevated temperature, the ultraviolet effect, and weathering actions. The weatherability of the plastic materials is critical, and currently an accurate picture for all films under all conditions is not available. Edlin and Willauer have projected the lifetimes of three unsupported films exposed to Florida weather--Teflon, 20 plus years; Tedlar, 9 years; and Mylar type W, 4 years (ref. 13).

Transmission of both glass and plastic covers is affected by dirt on the plates, pitting due to bombardment by sand, aging (ultraviolet effect in certain plastics), etc.

## (2) Absorber Plate

Kirchoff's Law states that the absorptance at any wavelength,  $\alpha$ , is equal to the emissivity,  $\epsilon$ , at that wavelength. This is true of conventional nonselective coatings, such as flat black paint. To reduce radiation losses from conventional absorbers, selective surface coatings have been developed. Basically, a selective surface is one whose emissivity is a function of wavelength. For example, if a surface has a high absorptance for solar radiation (wavelengths shorter than 2.5 microns) and has a low emissivity at longer wavelengths where reradiation takes place, then it will operate at higher temperatures and efficiencies than conventional absorbers. The basic mechanisms for selectivity, include: (1) variation of the index of refraction and index of absorption, (2) surface roughness of dimensions large relative to solar energy wavelengths, but small relative to long wave radiation, (3) layers of small particles of dimensions larger than solar wavelengths but smaller than long wave radiation, (4) thin anti-reflection films that increase absorptivity, and (5) thick semiconductor films, opaque to shortwave radiation, but transparent to long wave radiation, placed over metal substrates that have low emissivity. Combinations of the above structures and effects also act to produce selectivity (ref. 13).

The utility of selective surfaces in solar collectors is a function of two major factors. First, low long wave emittance is usually obtained at some sacrifice of high solar absorptance, and evaluation of this net effect of selectivity on the collector performance must be made for both the collector and final process. Secondly, solar collectors must be designed to operate for many years. The surfaces are exposed and operate at relatively high temperatures. Unfortunately test data for the absorptance and emittance of various surfaces are normally available for newly prepared surfaces, and only limited data are available for those surfaces of collectors after fairly long periods of operation (ref. 14).

At the present time it appears that good conventional coating (flat black paint) may be as good as any selective surface (especially if collector is not evacuated) if the collector is used for space conditioning purposes. This is based primarily on lack of performance data of selective blacks for extended periods of time as well as simple economics.



Honeywell and NASA have recently reported selective surfaces having absorbtivity/emissivity ratios of 13 and 18, respectively, and in 2 to 3 years, such surfaces may be economical with satisfactory performance longevity (ref. 12).

The greatest potential use of selective surfaces for flat plate collectors is in certain cooling applications and mechanical power generation. Tests of flat plate collectors utilized as a heat source for mechanical power generation generally give unsatisfactory results; however, the advent of an inexpensive, high quality selective surface would increase the useable collector temperature and thereby make moderate efficiency possible (ref. 14).

### (3) Problems in Collector Design

The preceding discussion has only included the major components of a flat plate collector, and this should be sufficient for this study; however, an item which has not been but should be discussed is the practical consideration in the manufacturing, shipping, installation, and actual use of flat plate collectors. These problems have by no means been solved but rather should be mentioned in any discussion of flat plate collectors. In looking at the design, manufacturing, and operation of the collectors, primary emphasis must be on the final cost of the delivered useable energy. A selective coating or an additional cover plate may indeed increase the thermal performance but will also undoubtedly increase the collector cost. The rudimental design choices such as tube in shecc and roll bond, can only be made when compared to the ultimate cost of delivered energy.

Other problems such as thermal stress breakage of cover plates when the working fluid is not being circulated to withdraw the collected heat, and operation in freezing climates with the option of draining or adding antifreeze must be considered. The elements--wind, hail, sandstorm, rain, and snow--must also be addressed. Accessibility and maintenance are also important aspects which are especially important to the Base Civil Engineer work force.

Westinghouse Electric Corporation, in a study for the National Science Foundation/RANN, has outlined the basic problems which must be considered in final collector and system design (ref. 12):

#### (a) Freezing and Boiling in Water Heater Collectors

A collector can be drained at night to prevent freezing, but this aggravates corrosion problems and sometimes causes problems in completely and automatically refilling all tubes to assure even flow. The fluid can be

charged with an antifreeze (ethylene glycol is most commonly mentioned) solution, but this requires a separate heat exchange loop to storage if the system is using water storage. It has been suggested that slow circulation from storage could be used to prevent freezing, but it has not yet been shown what effect on system performance this might have (additionally, a pump failure could then have disastrous effects on the collector). Boiling causes problems in a tightly sealed system, yet it is desirable to have a sealed system from the corrosion standpoint. The system may have to be designed to withstand the pressures attending the highest temperature the collector can reach; for 300°F this is about 59 psia, with no safety factor. Over-temperature relief systems, such as steam release; increased convection cooling, and shading, should probably be designed into a collector, because designing and building the collector to hold the required pressure could cause safety hazards.

#### (b) Corrosion

Copper tubing may be used to prevent corrosion in a water collector, but copper is expensive. Aluminum and steel are the next choices, but both of these materials are subject to corrosion. Suitable inhibitors may be used to prevent corrosion, but at present, the inhibitors are somewhat less than satisfactory for aluminum. The corrosion problem is aggravated by draining, since the metals are then exposed to oxygen in the air.

#### (c) Damage by Heating

Materials in contact with the absorber surface need to withstand temperatures (perhaps 200°C) which might be encountered as a consequence of lost fluid circulation. High temperatures can also cause degradation of selective absorbing surfaces.

#### (d) Damage by Hail

Since nearly all collectors considered to date (and likely to be considered in the near term) have glass covers, glass breakage could be an important consideration in some locations. Double strength glass can be used to resist breakage, but this glass is, of course, more expensive. Even so, it is important to construct the collector so that the glass can be easily replaced, and so that it is well supported and not in too large sections. Architectural standards would apply here.

## (e) Contamination in Air Collectors

Dust, moisture, and pollutants will circulate through an air heating collector and can conceivably cause surface deterioration, clogging of small passages, etc. This, of course, becomes serious if an air heating collector makes use of a selective surface, since selective surfaces are often delicate to begin with.

## (f) Deterioration of Paints and Other Materials

Since the collector in a system will involve a high capital investment, it is desirable to design for at least a 20 year life. The relatively high temperature environment inside the collector poses special problems in materials. A black paint (which might be used to avoid instabilities of a selective surface) could become faded, cracked, etc., in the long term. Therefore, special materials must be used, or simple maintenance procedures must be provided.

## (g) Heat Transfer Fluids

Air and water have been mentioned as the most suitable heat transfer fluids. Water must be protected from freezing, and as a result the heat carrying capacity is reduced 10 to 20 percent. Other liquids could be considered for heat transport from the collector. Any of them would have a lower specific heat than water, often half or less, but some have higher boiling points (lower vapor pressures) and may also have lower freezing temperature. With liquids other than water, the freezing is not likely to damage the collector because they shrink when freezing.

## (4) Possible Collector Configurations

Tables 4 and 5 list the configuration/operation variables for water and air heating collectors, respectively. It must be pointed out that these variables, the aforementioned seven special considerations, and the climatic conditions for a particular site must be analyzed to determine which configuration is the most desirable and practical for that location. The table is basic but illustrates the major options available in collector design. Table 6 also shows a few special collector configurations with their developer in parentheses (ref. 12).

## b. Storage

Solar energy is a time dependent energy resource, as are general energy needs. Unfortunately, the time dependence is not compatible; consequently, it is necessary to provide a means by which thermal energy collected during periods of

Table 4  
CONFIGURATION/OPERATION VARIABLES FOR WATER HEATING  
COLLECTORS (REF. 12)

- 
- A. Absorber Geometry
    - 1. Tube in Plate
    - 2. Tube below Plate
    - 3. Tube above Plate
  - B. Absorber Surface
    - 1.  $\alpha = 0.95$ ,  $\epsilon = 0.95$
    - 2.  $\alpha = 0.9$ ,  $\epsilon = 0.2$
    - 3.  $\alpha = 0.95$ ,  $\epsilon = 0.1$
  - C. Absorber Loss Control Variations
    - 1. Flat Plate
    - 2. Transparent Honeycomb
    - 3. Reflective Honeycomb
    - 4. Vee Corrugations
    - 5. Evacuation
  - D. Cover Plates (Glass or Plastic)
    - 1. 1 Cover
    - 2. 2 Covers
    - 3. 3 Covers
    - 4. 4 Covers
  - E. Cover Plate Spacing
    - 1. 1.0 cm
    - 2. 2.0 cm
    - 3. 3.0 cm
  - F. Back Insulation Thickness
    - 1. 5 cm
    - 2. 7.5 cm
    - 3. 10 cm
  - G. Fluid Flow Rate
    - 1. Slow (Laminar-near maximum collector temperature)
    - 2. Medium (Laminar-medium collector temperature)
    - 3. Fast (Turbulent-small fluid temperature increase)
  - H. Deployment-Tilt Angle
    - 1. Fixed Horizontal
    - 2. Fixed Vertical
    - 3. Fixed Tilt (Choice of tilt depends on emphasis toward summer or winter load)
    - 4. Periodic Tilt Adjustments (2 to 4 times per year)
  - I. Fluid Choice
    - 1. Water
    - 2. Water and Antifreeze
    - 3. Organic Liquid
-

Table 5

CONFIGURATION/OPERATION VARIABLES FOR AIR HEATING COLLECTORS  
(REF. 12)

- 
- A. Absorber Geometry
    - 1. Flat Surface
    - 2. Overlapped Surfaces
    - 3. Vee Surface
    - 4. Porous Bed
    - 5. Finned Surface
  - B. Air Flow
    - 1. Single Pass above Plate (or through porous plate)
    - 2. Single Pass below Plate
    - 3. Two Passes (in "series")
    - 4. Two-sided Pass ("parallel")
  - C. Absorber Loss Control Variations
    - 1. Transparent Honeycomb
    - 2. Reflective Honeycomb
    - 3. Evacuated Spaces
  - D. Cover Plates (Glass or Plastic)
    - 1. 1 Cover
    - 2. 2 Covers
    - 3. 3 Covers
    - 4. 4 Covers
  - E. Cover Plate Spacing
    - 1. 1.0 cm
    - 2. 2.0 cm
    - 3. 3.0 cm
  - F. Air Flow Rates
    - 1. Laminar
    - 2. Turbulent
    - 3. Fully Turbulent
  - G. Deployment-Tilt Angle
    - 1. Fixed Horizontal
    - 2. Fixed Vertical
    - 3. Fixed Tilt
    - 4. Periodic Adjustment
-

Table 6  
SPECIAL CONFIGURATIONS AND REFERENCES (REF. 12)

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Water Heaters

1. Evacuated Tubes - (Speyer)
2. Evacuated Space - (Blum, et al.)
3. Cylindrical Absorber - (Vineze)
4. Packed Bed Absorber - (Swartman)
5. Semitransparent Plate - (Lumsdaine)
6. Roof Pond - Movable Insulation - (Hay and Yellot)
7. Open Channel - (Thomason)
8. Combined Heating and Storage - (Zomeworks Corp.) (Harris)

Air Heaters

1. Overlapped Glass - (Löf)
  2. Parallel Foil Fins - (Bevell and Brandt)
  3. Double Exposure - (Safwat, Souka, Saini)
-

sunshine can be stored for use at night or on cloudy days. The optimum capacity of an energy storage system is dependent on solar radiation availability, the type of process loads, required reliability, and the determination of the percentages of the total load to be carried by solar and an auxiliary energy source (ref. 14).

The available methods of energy storage include sensible heat, latent heat, and chemical energy. Sensible heat storage systems utilize the solar energy collected to raise the temperature of a storage medium without a phase change of the medium material. The heat storage capacity of such a system is determined by the specific heat and density of the medium. Latent heat of fusion storage systems utilize the solar energy collected to actually produce a phase change in the storage material. In this case, the storage capacity is determined by the heat of fusion and density of the storage material. When photovoltaics or photochemical processes are used, storage is normally in the form of the chemical energy of reactants in a reversible chemical reaction.

In the design of solar energy systems the designer normally has alternatives as to the location of the storage component. For example, consider the process where a heat engine converts solar energy into electrical energy; storage can be provided as thermal storage between the solar collector and the engine, as mechanical storage between the engine and the generator, or as chemical storage in a battery between the generator and the end application. Solar cooling with an absorption air conditioner is yet another example. Thermal energy can be stored from the collector to be used by the air conditioner when needed or alternatively, the cooling produced by the air conditioner can be stored in a low temperature thermal storage unit. It must now be pointed out that the alternative storage component location is by no means equivalent in either capacity, costs, or effects on overall system design and performance. In the solar cooling example, the capacity required in a unit storing energy from the collector is less than that of a unit storing the cooling capacity from the air conditioner. This difference is approximately equal to the efficiency of the converter, i.e., air conditioner. Therefore, if the air conditioner is operating at 25 percent efficiency, the cooling capacity storage unit must be only about 25 percent of the capacity of the unit storing the thermal energy from the collector. The choice between these two storage locations may have very different effects on the operating temperature of the collector and correspondingly on collector size and ultimately on cost (ref. 12).

There are four major factors that should be examined closely during the evaluation of the various storage mediums (ref. 12): (1) Relation to building structure and cost of the thermal energy storage (TES) unit, (2) Storage capacity and unit volume, (3) Cycling life, and (4) Material cost and availability.

The storage temperature and unit volume are determined by the storage capacity of the material. Cycle life is important because many materials--especially phase change materials--exhibit marked changes in their physical or chemical structure after undergoing numerous heating and cooling cycles. For this reason many phase change materials must be frequently replaced.

#### (1) Sensible Heat Storage Materials

Sensible heat storage is currently the most reliable storage technique. The two most frequently used materials are water and rock. These materials are inexpensive and available throughout the country.

##### (a) Water

Water is currently used in approximately 70 percent of the TES systems using sensible heat. Freezing in the collector can be prevented by the addition of ethylene glycol; however, corrosion inhibitors should normally be added also. The use of glycol has two major effects on the system: (1) A heat exchanger is required between the collector loop and storage system as a result of the high cost of antifreeze, and (2) Ethylene glycol reduces the specific heat of water. Stratification (thermal differential over vertical dimensions of the tank) in the storage tank is another aspect which must be considered in analyzing storage capacities and energy balance equations must be written for each section--three sections appear to give fairly accurate results providing that the water enters at a low velocity (ref. 12).

##### (b) Rock

Rock or gravel TES units with air as the working fluid have been used in several demonstration houses because of simple installation, reliability, and low maintenance. As with water, these materials are low in cost and readily available throughout the country. The major disadvantages are the higher operating temperatures and corresponding lower collector efficiencies dictated by large temperature drops which often occur when air is used as the working fluid. Rock storage is also only about 30 to 40 percent as efficient per unit volume as water. This is due to a lower specific heat (0.2), a specific gravity of 2.7, and necessity of fairly large spaces between the rocks for the circulation of air. The



primary advantages are the high heat transfer coefficient between the air and rock, and the low conductivity of the rock bed when air flow is absent (ref. 12).

Table 7 shows the thermal capacity of typical sensible heat storage materials.

## (2) Latent Heat Storage Materials

Materials which undergo a phase change in a suitable temperature range may be very useful for energy storage. Due to constraints in volume and pressure vessels, the most suitable phase change for TES in facility applications is the solid-liquid transition. Melting, with high heat of fusion, occurs in a suitable temperature range in several materials. First of all, the temperature ranges for TES in space conditioning applications are shown in table 8 (ref. 14).

In examining any potential TES candidate, certain important criteria must be satisfied (ref. 15).

### (a) Thermodynamic Properties (Equilibrium)

The material should have a melting point within the temperature range of heating and cooling. While this seems to be quite obvious, it will be found later that many materials tend to supercool on cooling, such that their effective solidification temperature falls below the temperature range of cycling. This makes them useless as thermal energy storage materials.

The material should have a large heat of fusion. Obviously the larger the heat of fusion, the better the material. Thermodynamically however, heats of fusion are not very large compared to heats of vaporization; thus water has one of the largest heats of fusion per unit mass (80 cal/gm, 144 BTU/lb) and this probably constitutes an upper limit. All the materials considered so far have much lower heats of fusion ranging from 50 to 75 percent of that of water for equal mass.

The material should have a congruent melting point. Briefly this means that the material should melt completely at a fixed temperature or within a very narrow range of temperature (at most 5°C or 9°F). Otherwise, the difference in densities between solid and liquid will cause segregation, resulting in changes in the chemical composition of the material. This introduces complications in the cooling behavior.

Table 7

## THERMAL CAPACITY OF STORAGE MATERIALS (REF. 12)

Material	Specific Heat	Heat Capacity		Density	
		BTU/ft <sup>3</sup> /°F	kJ/m <sup>3</sup> °C	lb/ft <sup>3</sup>	kg/m <sup>3</sup>
Water	1.00	62.5	4,190	62.5	1,000
Water-Ethylene Glycol Mixture (30 to 70 percent by weight), at 230°F	0.80	51.2	3,440	64.1	1,025
Concrete	0.156	22.4	1,490	144	2,310
Scrap Iron	0.12	54.0	3,630	450	7,230
Rocks (crushed)	0.20	20.0	3,350	100	1,601
Marble (solid)	0.21	34.2	2,280	162	2,600
Rock Salt	0.219	29.6	1,985	136	2,180
Sand	0.191	18.1	1,215	94.6	1,533
Stone (quarried)	0.20	19.0	1,275	95	1,540

Table 8

## TEMPERATURE RANGES FOR THERMAL ENERGY STORAGE (REF. 14)

Application	°C	°F
Air Conditioning	5 to 15	41 to 59
Solar Heating	45 to 55	113 to 131
Absorption Refrigeration	90 to 120	194 to 248

(b) Kinetic Criterion

The material should not supercool. On cooling the TES material while in the liquid phase, the melt should solidify at the thermodynamic melting point. This requires a large rate of nucleation and growth. Otherwise, the liquid will supercool and ultimately form a glass, and the stored energy will not be released.

(c) Intrinsic Stability and Compatibility Requirements

The material should be stable. All applications to be considered in this report are long term thermal energy storage materials. The envisaged lifetime of such a system is of the order of 20 years. Hence, the materials to be used should be very stable and not tend to decompose into other materials. This is particularly critical for TES materials at high temperatures in the liquid state, since the diffusion of atoms is enhanced, and the rates of chemical reactions generally increase in these conditions. The possible reactions should be investigated from the thermodynamic and the kinetic points of view to determine whether they should be taken into consideration or can be safely ignored.

The material should not interact with the container. In addition to the required stability within the material itself, there also should be no material-container interaction. There is a sufficiently wide choice of available container materials today, including plastics, aluminum alloys, and ferrous alloys, that this point should not constitute a serious limitation.

The material should not be dangerous. Since the possibility of accidental leakage is always present, it is preferable to choose a material that is non-flammable, non-toxic, and not having a bad odor. It should be pointed out that leakage need not be catastrophic, involving rupture of the container; it can be a slow leakage through the container material (especially if it is a plastic) or through joints, welds, etc., in the structure.

(d) Economics

The material should be cheap and available. This point is not very well defined. The present cost of a material that is presently available may be much higher than the cost of the same material if a sufficiently large demand were generated for that material or if a more economic way of producing it were found. This point is well illustrated by the price of aluminum metal

in the past 80 years. Of course the ultimate cost is related to the availability of the material, or of its primary elements. The choices then should be confined to common materials, unless there is a compelling need to use a rarer or more expensive material, i.e., some form of "miracle property."

### (3) Phase Change Materials

Chemical classes of materials considered for storage in space conditioning systems include inorganic salt hydrates and their eutectics, organic compounds and their eutectics, clathrate hydrates, and inorganic-organic eutectics.

#### (a) Salt Hydrates and Eutectics

Numerous salt hydrates have been considered for heat storage. Glauber Salt (sodium sulfate decahydrate) has received the most attention, and its performance is characteristic of the vast majority of salt hydrates. In general, the materials melt incongruently and separate into a saturated solution with part of the anhydrous salt remaining undissolved and precipitating to the bottom of the container. On cycling, this two phase mixture will not completely return to the hydrate form, and it progressively deteriorates the latent heat storage capacity of the material with repeated cycling. Researchers at the University of Pennsylvania have attempted to prevent this settling with various techniques to include encapsulation, thickeners, and foams, but none were successful. Upon going through numerous freeze-thaw cycles, the salt continued to show a decline in its latent heat capacity and did not reach an equilibrium latent heat value. Therefore, it was recommended that Glauber Salt not be used for TES systems. In general, there are many salt hydrates which have not yet been investigated; however, much work remains to be done on nucleating agents and means to prevent settling prior to utilizing salt hydrates for thermal energy storage (ref. 8).

#### (b) Organic Compounds and Eutectics

Organic materials which have been investigated include natural and artificial spermaceti, paraffin waxes, and methyl laurate. The paraffin waxes appear to be promising, with the major drawbacks being that their phase change is accompanied by an approximate 10 percent change in volume and that they exhibit supercooling as do the salt hydrates. The choice of containers requires careful consideration, since, for example, environmental stress cracking makes polyethylene and polypropylene incompatible with paraffin. Aluminum or

steel containers would most likely have to be used. SUNOCO P116 and Enjay C15-16 paraffin waxes currently have the greatest potential for TES systems.

#### (c) Clathrate and Semi-Clathrate Hydrates

Clathrate hydrates have not received much attention until recently, but preliminary results are promising. A few clathrates are immediately unsuitable due to chemical activity, corrosion, and requirement for pressurization. Clathrates found suitable thus far for air conditioning TES include trimethylamine, tetrabutylammonium formate, and tetrabutylammonium acetate. A successful nucleating agent has been found for the tetrabutylammonium hydrate, whereas the other clathrates do not require such agents. Additional investigations are required for clathrate hydrates but these materials definitely show promise (ref. 13).

#### (d) Organic-Inorganic Eutectics

Very little work has been accomplished in studying this class of materials. The Russians have performed some research with urea and acetamide eutectics, but data are inconclusive, and additional investigation should be accomplished (ref. 15).

Table 9 shows the most common salt hydrates and paraffins used in TES studies. Clathrates and organic-inorganic Eutectics are not included due to insufficient heat of fusion data (ref. 8).

#### (4) Other

One other TES system which must be mentioned is the use of desiccants. Thermal storage can be achieved by using the heat of adsorption in a desiccant material which adsorbs water from an air-water vapor mixture. Promising materials include crushed gravel soaked in a solution of lithium chloride or calcium chloride. Silica gel probably possesses the greatest potential but is too expensive. Further experimental investigation is a must for these systems (ref. 8).

#### (5) Summary

The only thermal energy storage systems which can be recommended at the present time are water, or water-ethylene glycol mixtures, and paraffins--both are safe, reliable, inexpensive, and readily available.

Table 9  
PHASE CHANGE THERMAL ENERGY STORAGE MATERIALS (REF. 8)

Materials	Melting Point		Heat of Fusion		Heat Capacity	
	F°	C°	BTU/lb	kJ/kg	BTU/ft <sup>3</sup>	kJ/m <sup>3</sup>
<u>Salt Hydrates</u>						
$\text{Na}_2\text{SO}_4 \cdot 1/2\text{NH}_4\text{Cl} \cdot 1/2\text{NaCl} \cdot 10\text{H}_2\text{O}$	55	12.8	78	181	7200	268,265
$\text{K}_2\text{HPO}_4 \cdot 6\text{H}_2\text{O}$	52 to 56	11.1 to 13.3	47	109	4900	182,570
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	117	47.2	66	154	7650	285,032
$\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$	113 to 120	45.0 to 48.9	90	209	9200	342,784
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ (Glauber Salt)	90	32.2	108	251	9900	368,865
$\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	239	115	71	165	6940	258,578
<u>Waxes</u>						
C14-C16 Paraffin	35 to 45	1.7 to 7.2	65.4	152	3185	118,670
C15-C16 Paraffin	40 to 50	4.4 to 10.0	65.7	153	3200	119,229
C14 Paraffin	35 to 40	1.7 to 4.4	71.1	165	3420	127,426
C16 Paraffin	58 to 65	14.4 to 18.3	86.2	200	4190	156,116
P116 Paraffin	116	46.7	90	209	4380	163,195

Continued research in other latent heat storage systems must address the following problems if such systems are to be competitive in the future (ref. 12): (a) instability of solution under cycling, (b) tendency to supercool requiring nucleating agents, (c) low thermal conductivity of solid phase, reducing the heat transfer, (d) shrinkage of solid phase from containment vessel, further reducing heat transfer, and (e) high cost of containment vessels, tanks, and materials.

### c. Solar-Powered Air Conditioning

The use of solar energy to drive cooling cycles has been considered for two purposes--refrigeration for food preservation and comfort cooling. Discussion of cooling in this section will deal with the operation of air conditioning equipment utilizing the same flat-plate collectors that are used for space and water heating. The basic systems which have been studied are: (1) absorption systems, (2) Rankine Cycle-vapor compression systems, (3) Jet Ejector Systems, (4) Adsorption Systems, (5) Rankine Cycle--inverse Brayton Cycle Systems, and (6) Night Radiation Systems. The gas absorption and vapor compression (heat pump) systems are the most promising approaches at the present time, and will be examined in some detail. A rather new and unconventional system based on air dehumidification will also be discussed. Prior to discussing these systems, mention should be made to the night radiation concept. There are a few solar heated facilities which utilize nocturnal cooling through either evaporation or radiation, or both. The most efficient systems do not utilize the solar collector for radiation because a well designed collector should be a poor radiator. These systems are not discussed in detail because they are geographically limited to those high altitude installations with very dry climates, but it should be pointed out that such systems have a definite potential at certain installations in the southwest.

#### (1) Gas Absorption

The only direct technique for producing refrigeration from a heat source is through absorption refrigeration. A solution of refrigerant and absorbent, each having a strong chemical affinity for the other, is heated in the high pressure portion of the system (generator). This operation drives a portion of the refrigerant out of solution and the hot refrigerant is then cooled until it condenses and can be passed through an expansion valve into the low pressure section of the system. This pressure reduction through the expansion valve expedites the vaporization of the refrigerant which in turn effects

the removal of heat from the environment. The vaporized refrigerant is then recombined with the original absorbent-refrigerant mixture and creates a mixture which is rich in refrigerant. The mixture is pumped back into the high pressure side of the system and is subsequently heated so that the cycle continues.

Currently available absorption refrigeration machines utilize lithium bromide and water, or ammonia and water, as the working fluids. In lithium bromide/water machines, water is the refrigerant, and the salt solution of lithium bromide is the absorbent. The water/ammonia machine uses ammonia as the refrigerant and water as the absorbent. Table 10 shows a basic comparison of the two machines. The lithium bromide/water system is generally a better machine than the ammonia/water system for the following reasons (ref. 8):

- (a) The higher temperature requirement of the ammonia/water systems places more stringent requirements on the solar collector.
- (b) Poorer theoretical performance (COP) for ammonia/water system.
- (c) Higher pressures and corresponding higher pumping power requirements for ammonia/water.
- (d) Ammonia/water system is more complex in that it requires a rectifier to separate ammonia and water vapor at the generator outlet.
- (e) The toxic characteristic and other potential hazards associated with ammonia act as a deterrent to residential use, and these systems are restricted from in-building applications.

Absorption refrigeration units are commercially available through Trane, Carrier, York, Bryant, and Arkla-Servel. Trane, Carrier, and York only manufacture LiBr/water units with nominal capacities greater than 100 tons. Bryant produces gas fired, aqua/ammonia systems up to 10 tons. Arkla-Servel markets both aqua/ammonia up to 10 tons and LiBr/water units ranging from the 3 ton Arkla Model 501 to units greater than 100 tons. Arkla LiBr/water units can be either steam or hot water fired.

## (2) Rankine Cycle--Vapor Compression Systems

The heat pump or vapor compression cycle is the most commonly used means of providing cooling today. It is used in space comfort cooling as well as for food refrigeration, and units are available over the range from 1 to 8000 tons. Unfortunately, the heat pump does not have a very good reputation in the



Table 10  
SYSTEM COMPARISON (REF. 8)

Capacity	3-1600 Tons	2-10 Tons
Generator Input Temperatures	180-260°F (82-127°C)	250-300°F (121-149°C)
Cooling Coil Temperature	45°F (7°C)	5°F (-15°C)
Coefficient of Performance	0.5-0.8	0.4-0.6
Water Cooling Required	Yes	No
Pressure Range	0.2-2.2 psia	70-350 psia
Corrosive Working Fluid	Yes	Yes
Cost (Initial)	\$325/Ton at 3 Ton Including Cooling Tower	\$250/Ton at 3 Ton
Flammable Refrigerant	No	Yes
Toxic Refrigerant	No	Yes
US Building Code	No	Yes
Restrictions on Indoor Applications		
Flammable Absorbent	No	Yes
Salt Precipitation	Yes	No
Latent Heat of Vaporization	High	High

Department of Defense, who was one of the largest purchasers of the first generation of domestic air-to-air heat pumps. Their experience was unfavorable to say the least, and the units were plagued by numerous minor problems. The reason for the poor performance of the first generation heat pump was due to the premature use of inadequately tested equipment. Today the heat pump, in its third generation form, has proven itself to be a reliable and versatile device having overcome the many problems encountered in the earlier models (ref. 8).

The solar-assisted heat pump has proven its flexibility in three major applications. These include systems of bare collectors in Tokyo and Tucson, which demonstrated the heat pump in climates with a severe winter and a very warm summer, respectively. Bridgers and Paxton also demonstrated a system using a single glazed collector a conventional water-to-water heat pump, and small evaporative cooler in their office building in Albuquerque,

One of the disadvantages of the heat pump is that, as the ambient temperature varies from the design point, the performance is lowered. This is readily apparent in winter operation. The major advantages of a heat pump in solar systems is its inherent ability to function with a temperature source significantly lower than that of the space to be heated. This permits the collector to operate at lower and more efficient temperatures and allows the selected energy storage system to operate throughout a wider temperature range. One of the most critical aspects of system selection is the cost effectiveness of the glazed versus the unglazed collector. This must be closely studied for each installation with primary concern being the ability of the glazed system to utilize solar heat directly offset against the cost and water consumption of the evaporative cooler heat sink during the cooling operation (ref. 8).

### (3) Desiccant Cycle Cooling Systems

Another method of providing space cooling which is rather different from the conventional approach to solar-powered air conditioning systems is based on air dehumidification cycles. This method is primarily designed for hot and humid regions which also experience high solar insolation. It must be pointed out, however, that a simple modification also makes the unit attractive for hot and dry climates. A psychrometric chart showing its operation schematically is shown in figure 8. Warm air from the building in state 1 is dehumidified by a desiccant such as a rotating silica gel bed or a tri-ethylene glycol spray and becomes heated in the process to state 2. Then the hot dry air in state 2 is

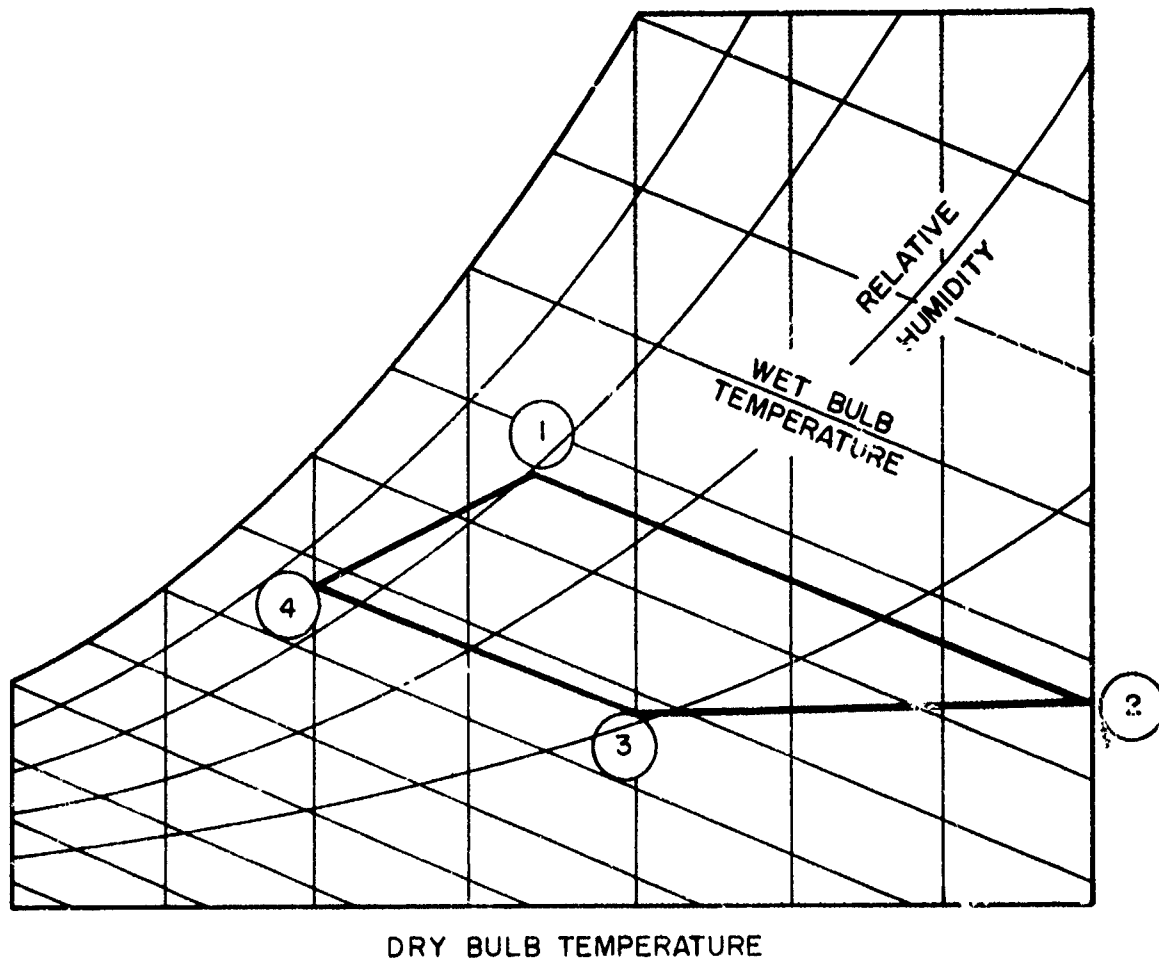


Figure 8. Operating Cycle of Air Conditioning System Based on Dehumidification (Ref. 8)

cooled to state 3 by outside air while passing through a heat exchanger. Here the dry air emerging from the heat exchanger will have a temperature slightly above outside air dry bulb temperature. Next, the air in state 3 is cooled by an evaporative cooler (humidifier) to state 4. Air in state 4 is returned to the house. One of the disadvantages of a desiccant system is its large size since it must circulate vast amounts of air, and it requires quite a few large components and heat exchangers. In addition, it is impossible to make a fair comparison with other systems due to limited performance data on the desiccant units (ref. 8).

Advantages include its excellent adaptability to solar energy utilization. Solar energy can be readily used to heat the air required to regenerate the desiccant. Regeneration of silica gel and tri-ethylene glycol requires temperatures of 150° to 170°F, and these temperatures are considerably lower than those required for the operation of gas absorption systems (ref. 8).

#### d. Research Requirements

Although the state-of-the-art in solar heating and/or cooling has progressed at an exceptional pace in the last few years, there are several areas which need further research and engineering development to make solar energy competitive with conventional systems (ref. 12):

##### (1) Collectors

- a. Corrosion control which is safe and inexpensive must be provided for the water filled absorber--especially those constructed of steel or aluminum.
- b. Removal of heat from water filled collectors when there is no flow.
- c. Selective surfaces which are inexpensive, exhibit high absorptivity and a relatively high absorptivity/emissivity ratio, and will have a long life expectancy.
- d. Collector design which is economical, efficient, and pleasing.

##### (2) Storage

- (a) Latent heat storage materials that melt at temperatures in the range of 130° to 160°F for heating and 30° to 40°F for cooling system storage. Such materials must be capable of a long cycling life as well as low cost.

(b) Designing for the maintenance of good water storage tank stratification to permit heat withdrawal at a constant temperature and at a constant rate.

(3) Air Conditioning

(a) Continued investigation of various combinations of absorbent and refrigerant which may perform better at lower temperature than the lithium bromide/water system.

(b) Improvement of absorption system reliability.

(4) System

(a) Further develop economical and reliable controls to operate complex solar systems efficiently.

(b) Refine heat pump for efficient operation when utilizing water between 35° and 110°F.

The most critical areas for immediate research are corrosion in collectors, system controls, and collector design.

e. Potential of Solar Heating and Cooling at Air Force Installations

The first step in determining the general feasibility of solar heating and/or cooling at CONUS locations was to select a representative sampling of bases. This was done by looking at climatic classifications and the location of stations reporting hourly solar insolation values.

Climatic areas were first quantified by Köppen's Classification System. Each climatic type is basically a function of rainfall and temperature variation. Depending on the detail desired, the CONUS can be subdivided into anywhere from four to possibly twenty different classifications. Typically seven or eight divisions are shown on published climatic maps. The distribution of stations used in this report represents at least one sample from each of eight different climatic classifications which in turn represent all but a small portion of the high interior region of the Rocky Mountains.

The region east of the Rockies can be classified into four major climatic regions. From the Rocky Mountains westward the situation becomes quite complex because of large variations in elevation and relative positions of mountain ranges across short distances and because of the general westerly wind flow and proximity of the Pacific Ocean. Within California, for example, one can go from a

subtropical desert climate to a cold temperature climate. One station in California and one in Washington are examined but they are not to be taken as typical West Coast stations. For stations in the Rockies and on the West Coast, even more than in other areas of the country, each station must be examined on an individual basis.

Fourteen stations were selected for the basic study. These stations, together with heating and cooling degree day data and classic and descriptive climatic classifications, are listed in table 11. "C" refers to a warm, temperate, rainy climate; within the CONUS, "C" covers most of the region east of the Rockies and south of 40°N latitude as well as most of California and the western third of Oregon and Washington. "D" is a cold, temperate climate, and covers the remainder of the eastern part of the CONUS, as well as parts of the higher elevations of the Rockies. "BS" and "BW" are arid climates which are typical of most of the Rockies and their eastern slopes, the majority of the Southwest part of the CONUS, and the central California valley. "A" is a moist tropical climate which is restricted to the southern tip of Florida.

The General Electric Space Division has accomplished a feasibility and planning study for solar heating and cooling of buildings as part of a National Science Foundation/RANN contract. They analyzed solar potential at 12 cities of which 9 correspond to the Air Force installations listed in table 12. For each location, 17 facilities were modelled and characterized and the heating and cooling demand loads were determined. For relative comparison, General Electric chose a simple double-glazed, flat-black coated collector panel. Collectors were tilted at an angle of latitude plus 15 degrees. Average heat loss characteristics as well as absorption, emission, and transmissivity characteristics were used. The system selected for a preliminary evaluation consisted of a basic heat exchange system for heating and an absorption air conditioning system for cooling. An efficiency of 1.0 was assumed for the heat exchanger, and a coefficient of performance (COP) of 0.50 was assumed for the absorption air conditioner. Collector fluid temperature of 130°F and 180°F were utilized for the heating and cooling system, respectively. Based on a monthly average collector and system efficiencies for each location, the collectable solar energy per unit area was obtained for heating and cooling application at each location. The unit collectable energy values were used to establish the design functions for solar energy systems for each location. By considering the ratios of energy collected for

Table 11  
 REPRESENTATIVE CONUS INSTALLATIONS

Base	Annual Heating Degree Days	Annual Cooling Degree Days	Köppen Classification	Descriptive Summary of the Köppen Classification
Andrews	4551	1237	Caf	Warm, temperate, rainy climates with no noticeable dry period. For the coldest month $-30^{\circ}\text{C} < \bar{T} > 18^{\circ}\text{C}$ ( $-22^{\circ}\text{F} < \bar{T} < 64^{\circ}\text{F}$ ). Warmest month $\bar{T} > 22^{\circ}\text{C}$ ( $72^{\circ}\text{F}$ ).
Carswell	2301	2858	Caf	
Charleston	2205	2118	Caf	
Hanscom	6484	591	Caf	
Tyndall	1321	2753	Caf	
Mather	2600	1303	Cas	Summer dry season with $\bar{T}$ summer $> 22^{\circ}\text{C}$ ( $72^{\circ}\text{F}$ ).
McChord	5287	94	Cbs	Summer dry season with $\bar{T}$ summer $< 22^{\circ}\text{C}$ ( $72^{\circ}\text{F}$ ).
Offutt	6213	1157	Daf	Cold, temperate climate. No noticeable dry period. "a" indicates warmest month $\bar{T} > 22^{\circ}\text{C}$ ( $72^{\circ}\text{F}$ ).
Loring	9500	152	Dbf	
Kincheloe	9234	173	Dbf	
Minot	9614	398	Dbf	
Kirtland	4299	1464	BSk	Arid Steppe & desert climates $k \doteq \bar{T}$ annual $< 18^{\circ}\text{C}$ ( $64^{\circ}\text{F}$ ). $h \doteq \bar{T}$ annual $> 18^{\circ}\text{C}$ ( $64^{\circ}\text{F}$ ).
Williams/Luke	1497	2926	BWh	
Homestead	218	3906	Aw	Moist tropical climate with distinct winter dry season.

Table 12

## ANNUAL UNIT COLLECTABLE ENERGY FOR HEATING AND COOLING (REF. 15)

Base	Collectable Energy Heating (BTU/Ft)	Collectable Energy Cooling (BTU/Ft)	Heating Cooling	Design Application
Andrews	132,200	29,100	4.5	H & C
Carswell	140,100	68,700	2.0	H & C
Charleston	114,600	52,900	2.2	H & C
Harscom	88,100	14,100	6.3	H
Homestead	32,250	129,500	0.3	C
McChord	101,300	7,050	14.4	H
Minot	212,400	15,000	14.2	H
Offutt	178,000	28,200	6.3	H & C
Williams	179,000	86,000	2.1	H & C

NOTE: Based on T (Heating) = 130°F, T (Cooling) = 180°F baseline systems are heat exchanger and absorption air conditioner (COP = 0.50)



heating and cooling, the relative cost effectiveness between the two functions can be compared for a selected location. With the exception of Homestead, this ratio generally shows the relation of the cost effectiveness of purchasing solar driven air conditioning equipment. Heating and cooling were considered to be cost effective for those locations with a ratio of near unity, whereas those locations with large ratios were considered for heating only. Table 12 shows the collectable energy, heating to cooling ratio and the recommended system application. Of the 17 buildings selected for modelling, four are directly applicable to AF application--(1) residential (family housing); (2) Visiting Officer Quarters/Dormitories (low rise hotel/motel); (3) administrative/operations facilities (low rise offices); and (4) schools. These types of facilities also generally show the best potential for solar energy applications. Load savings for the four facility types at each of the nine locations are shown in table 13 and the percentages of heating and cooling load demands which can be met for the facilities and corresponding locations are shown in table 14. Although the modelled housing unit is larger than the average MFH unit, it still gives a general idea of the solar energy potential (ref. 15).

Solar heating and cooling of buildings have excellent potential for (1) military family housing units, (2) administrative/operations type facilities, and (3) schools. The BOQ/dormitory type facilities do not show as good a potential, but a few demonstration units should be planned for actual testing in a user-environment.

Another method of comparing solar energy potential was accomplished by assuming a heating load and determining the collector area required to meet this demand for each installation. For this sample calculation, a load demand of 100,000 BTU/day for the month of January was used. The mean January solar radiation values for each base was used for the solar input, and a system efficiency of 35 percent was assumed. Collector areas were then normalized to Kirtland AFB, with the following results:

ANDREWS	1.52	HOMESTEAD	1.06	McCHORD	2.66
CARSWELL	1.23	KINCHELOE	1.68	MINOT	1.41
CHARLESTON	1.32	KIRTLAND	1.00	OFFUTT	1.31
ENGLAND	1.37	LORING	1.56	TYNDALL	1.17
HANSCOM	1.62	MATHER	1.35	WILLIAMS	1.06

Table 13

ANNUAL HEATING AND COOLING LOADS SAVED PER BUILDING\* (X 10<sup>6</sup> BTU)

Base	Heating				Cooling		
	Military Family Housing	BOQ/Dorm	Admin/Operations	School	Military Family Housing	BOQ/Dorm	Admin/Operations
Andrews	64	1394	702	3832	14	323	161
Carswell	63	1500	754	4800	34	910	455
Charleston	105	1285	645	3870	52	683	342
Lg Hanscom	44	835	379	2295	8	142	71
Homestead	7	76	38	664	132	1898	950
McChord	50	707	351	2277	4	62	28
Minot	101	1812	901	4857	8	133	66
Offutt	93	1717	863	4819	14	289	142
Williams	97	1300	655	5872	85	1081	541

\*NOTE: Modelled facilities have following characteristics:

	No. of Stories	Floor Area (Sq ft)	Wall Area (Sq ft)	Window Area (Sq ft)	Height (ft)/Story
Family Housing	2	1,800	2,196	330	9
BOQ/Dorm	2	40,000	10,800	3,240	9
Adm/Ops	2	20,000	8,800	1,760	11
School	2	52,000	12,880	3,200	14

Table 14

## PRELIMINARY HEATING AND COOLING PERCENTAGES SUPPLIED BY SOLAR ENERGY

Base	Heating				Cooling		
	Military Family Housing	BOQ/ Dorm	Admin/ Operations	School	Military Family Housing	BOQ/ Dorm	Admin/ Operations
Andrews	46	9	50	57	12	14	15
Carswell	82	20	95	98	17	24	26
Charleston	84	18	91	84	20	18	19
L.G. Hanscom	24	4	21	25	10	10	11
Homestead	100	100	100	100	39	42	46
McChord	39	5	22	18	20	19	20
Minot	38	6	33	35	13	13	14
Offutt	49	8	44	50	11	12	13
Williams	86	31	100	100	26	29	34

This represents a rather crude comparison but does give a general idea of the larger magnitude of collector areas required for such sites as Hanscom, Kincheloe, and McChord.

Other analyses and comparisons can be made; however, unless a thorough computer analysis of hourly insolation values, heating and cooling demands, and storage efficiencies are accomplished for each site, these previous comparisons will suffice for the purpose of this report. Figure 9 matches solar energy application with general climatic data and should be used as a general guideline for determining where further studies should be accomplished.

#### f. Cost of Solar Heating and Cooling

Tables 15 and 16 show cost comparison of solar versus conventional heating and cooling at seven installations. The solar heating and cooling costs are based on the Löff and Tybout study (ref. 16), while gas, oil, and electricity are current costs at the particular installation. Water heating is included in solar system and solar costs are based on \$2 per square foot of collector, 20-year life cycle, 8 percent interest, and \$1,000 surcharge for absorption cooling.

### 3. SOLAR THERMAL CONVERSION

Solar Thermal Conversion Systems collect solar insolation and convert it to thermal energy and electric power. The heat absorbed is transferred to a working fluid for use in a solar thermal electric conversion system or in a solar total energy system. Solar thermal electric conversion systems utilize a thermodynamic cycle to convert solar energy to electrical energy with maximum efficiency. Waste heat is dissipated to the environment at the lowest practical temperature. Solar total energy systems utilize solar energy to generate electricity also; however, the waste heat is at a higher and useable temperature. The higher temperature of the rejected heat makes electricity generation less efficient than the solar thermal electric conversion system but then the useability of the waste heat makes the overall efficiency of the total energy system much greater (ref. 11).

A basic solar thermal conversion system consists of (1) a concentrator to focus the sun's energy; (2) a receiver to absorb the concentrated energy; (3) a means to transfer the heat to a thermal storage facility or directly to the turbo-generator; (4) a thermal storage element to store thermal energy for use at night and on cloudy days; and (5) a turbo-generator to produce electrical energy.

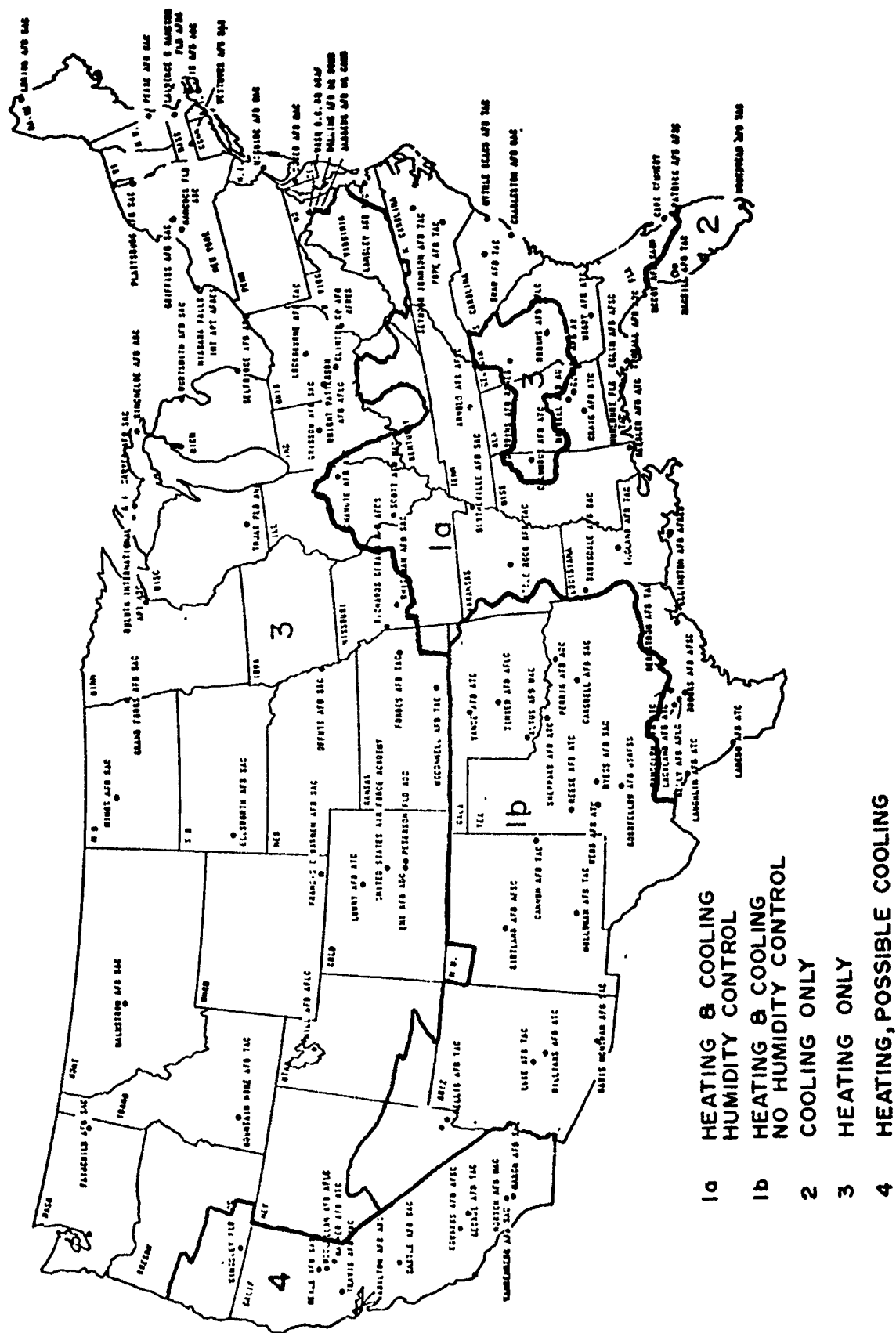


Figure 9. Solar Energy, Potential Region Classification (ref. 15)

Table 15  
SOLAR HEATING AND COOLING DESIGN OPTIMA FOR MILITARY FAMILY HOUSING UNIT (REF. 16)

Base	Collector Area	Storage (lb water/ft <sup>2</sup> of collector)	Number of Plates	Percent Load by Solar		Cost Combined Dollars Per MBTU	Cost Combined Dollar Per 100 kWh
				Cooling	Heating		
Charleston	1040	10	3	62	92	2.47	0.84
Hanscom	1040	15	2	66	64	3.07	1.05
Homestead	1040	10	3	58	100	2.13	0.73
Kirtland	520	10	2	56	73	1.73	0.59
Luke	1040	10	3	29	100	1.71	0.58
McChord	520	15	2	39	44	3.79	1.29
Offutt	1040	10	2	57	60	2.48	0.85
Vandenberg	260	10	2	27	64	2.45	0.84

collector tilt = latitude (except Homestead; tilt = latitude minus 10)  
 optimum criterion: least cost solar heat for combined use--hot water heating included  
 collector cost: \$2 per ft<sup>2</sup>  
 storage cost: \$0.05 per pound of water  
 other constant costs: \$375 per system  
 air conditioner cost: \$1,000 above conventional: C.O.P. solar to cooling 0.15  
 amortization: 20 years at 8 percent interest

Table 16

COST COMPARISON OF SOLAR VERSUS CONVENTIONAL HEATING AND COOLING  
SYSTEMS (ALL COSTS IN DOLLARS PER MBTU) (SOLAR COSTS TAKEN FROM REF. 16)

(Note: Gas Furnace Efficiency Assumed as 67 Percent)

Installation	Solar			Electricity			Gas		
	Heating	Cooling	Combined	1974	1980	1985	1974	1980	1985
Charleston	3.34	3.48	2.46	6.46	11.11	12.73	1.47	3.12	4.60
Hanscom	3.02	8.73	3.07	9.97	14.26	16.05	1.89	3.44	4.80
Homestead	14.64	2.25	2.14	6.37	10.96	12.55	---	---	---
Kirtland	2.08	3.28	1.73	3.52	5.28	6.16	0.47	1.13	1.60
Williams	2.87	2.05	1.70	6.33	9.50	11.08	1.34	3.03	4.57
McChord	3.13	19.59	3.78	1.49	2.24	2.61	1.16	2.62	3.96
Offutt	2.93	5.42	2.49	2.16	3.05	3.72	1.17	2.41	3.50
Vandenburg	1.58	14.58	2.46	4.04	6.06	7.07	1.43	3.23	4.88

#### a. Solar Collection

Collection of the solar energy can be accomplished by three basic devices: flat plate, linear focus, and point focus collectors. The major characteristics of each type are shown in table 17. As previously discussed, the flat plate collector is limited by its operational temperature capabilities and in general is not being considered for solar thermal conversion systems. In focusing collectors, thermal losses are reduced; however, optical losses and the loss of the diffuse component of the solar radiation become rather significant. There are also additional engineering problems such as capability of system to track the sun and difficulties associated with maintaining the required quality of the optical systems.

For the purpose of clarification of further discussion, "collector" will be applied to the total system including receiver and concentrator. "Receiver" is that system component where radiation is absorbed and converted to some other energy form, and includes the absorber, associated covers if applicable, insulation, etc. "Concentrator" (optical system) is that part of the collector which directs or focuses the radiation on the receiver (ref. 14).

As with the flat plate collector, the basic design requirements for the collector is that it be simple, reliable, inexpensive, easy to maintain, and have a relatively long life expectancy.

#### b. Linear Focus

Parabolic trough collectors have been fabricated by two primary methods. One method consists of sandwiching a flexible metal honeycomb between two outer skins of fiberglass/epoxy to achieve a self-supporting rigid structure of the correct parabolic contour. The second method uses the same mass production technique as does the fiberglass boat industry. These troughs consist of a fiberglass/polyester mixture sprayed over a male mold of the required parabolic contour. Integral ribs and flanges are provided for self-support when appropriate end plates are added. These two construction methods have been used to produce parabolic troughs as large as 9 ft x 12 ft. Other construction methods for fabricating smaller troughs include fiberglass/epoxy skins with honeycomb or foam interiors; fiberglass/polyester skins with foam or honeycomb; graphite composite/epoxy skins with foam or honeycomb; metal skins with honeycomb; self-skinning foam structures; and foamed lightweight concrete with polymer concrete skin (ref. 11).



Table 17

## CHARACTERISTICS OF SOLAR COLLECTOR SYSTEMS

(Ref. 11)

Type	Application	Collection Method	Tracking Requirement
Flat Plate	Low Temperature (typically 150°C)	Solar energy is absorbed directly on a surface with no concentration. Both the specular and diffuse components of the solar input are collected.	None
Linear Focus	Low to Moderate Temperature (typically 300°C)	Solar energy is concentrated to a "line" by means of a parabolic trough mirror or a linear Fresnel lens. Energy is then absorbed on the surface of a pipe and transferred to a fluid flowing within the pipe. Only the specular component of the solar input is collected.	Must track the sun in at least one dimension.
Central Focus	Low, Moderate, and High Temperature (up to 1000°C or higher)	A large number of nearly flat mirrors reflect solar energy to a central "point" at the top of a tower. The concentrated flux is then absorbed on a surface and transferred through the walls to a working fluid, or absorbed directly in a working fluid. Only the spectral component of the solar input is collected.	The mirrors must individually track the sun in two dimensions.

### c. Central Focus

The basic concept consists of flat mirrors used for point focusing solar radiation onto a central receiver. The flat mirrors used as heliostats for this concept have been constructed from float glass, rigid plastic sheets, and taut thin plastic films coated with reflective aluminum film (aluminum film is also coated for weather protection).

### d. Thermal Energy Transport Systems (Working Fluid)

The most commonly used methods of transporting thermal energy to electrical energy convertors include (ref. 11):

- (1) Boiling circulation of liquids (water).
- (2) Non-boiling forced circulation of liquids (water, fused salts, liquid metals, organic liquids).
- (3) Natural circulation of boiling or non-boiling liquids.
- (4) Forced circulation of gases such as air (in an open or closed loop) or helium (closed loop only).

### e. Thermal-to-Electrical Conversion Systems

Thermal-to-electrical conversion systems have been utilized for years. The steam turbine is used predominantly by the electric utilities to produce electricity from fossil or nuclear heat. The popularity of the gas turbine is increasing for power generation with primary use for peaking operation. Organic vapor turbines are being used more and more by chemical process industries to reduce power costs and these turbines show great promise for solar thermal conversion systems (ref. 11).

### f. Heat Rejection Systems

The electric utility companies have the greatest experience with once through water condensers and cooling towers. As environmental restraints and water resources become increasingly limiting, air condensers and air cooling towers are being gradually incorporated into utility practices.

A few U.S. and European utilities provide district heating to commercial and residential buildings in urban areas. The heating is often provided from the waste heat of steam turbine-generators. In order to raise the heat rejection temperature for more effective use of the waste heat, the units are not operated

at maximum electrical conversion efficiency. Such total energy systems can have higher overall thermal efficiency than an all electric generating station, depending on the relative mix of electricity and heat demanded by the users (ref. 11).

#### g. Energy Storage

Solar thermal conversion systems require some energy storage capability since, as discussed previously, solar insolation is variable. Of the various storage mechanisms, thermal storage is the preferred. As with solar heating and cooling of buildings, the development of a low cost storage system is a major challenge. The basic problems are the same with the major exception being the much higher working temperatures in the solar thermal conversion system.

Organic fluids show promise at low to moderate temperatures, up to about 450° to 500°F (230°C to 260°C). Water is limited by its containment requirements which increase with greater temperatures. At or above 600°F, neither water nor organic fluids appear to be satisfactory. Few organic compounds are stable at or above 600°F and water has a vapor pressure of 2000 psia at 600°F (ref. 11).

Fused salts are stable at temperatures of 1000°F and higher but often experience recrystallization and nucleation problems. Sodium also shows potential--being liquid at 208°F and not reaching atmospheric pressure until 1621°F. There are of course many other storage media which must be investigated to establish the best material for the required temperature and application (ref. 11).

#### h. National Program

The national solar thermal R&D program is looking at two major concepts: (1) Central receiver load-following electric power plan and (2) a total energy system. The first step required in the development of each concept is the construction of an operational test facility. Sandia Laboratories in Albuquerque, is developing the solar total energy test bed which will provide 200 kW thermal and 32 kW electric when completed. Partial test bed construction should be completed around July 1975 with total test bed scheduled for completion in July 1976. The central receiver will require a large [5 megawatts thermal (MWTH)] solar furnace test facility to evaluate experimental boiler/superheaters and other central receiver heat exchangers; and to provide a test site for the evaluation

of significant numbers of heliostats (reflectors, mirrors) and heliostat guidance and control devices to be used in central receiver power systems (ref. 17).

Large scale solar furnaces offer an excellent starting point for determining the desired characteristics of the central receiver test facility. There are five large scale solar furnaces in the world today. The United States Army solar furnace at White Sands Missile Range and the French Army solar furnace at Odeillo, France, are utilized for evaluating thermal shocks corresponding to nuclear weapon effects; whereas, the furnaces at Tohoku University, Japan and the CNRS Solar Energy Laboratory in France are used for metallurgy and high temperature physics. The fifth large scale solar test facility is used for the study of central receivers for steam generation at the University of Genoa, Italy. Two of these furnaces, the CNRS facility and the University of Genoa facility utilize multiple heliostats which are applicable to the central receiver concept. The University of Genoa test facility, under the direction of Professor Francia, represents an excellent parallel to the proposed U.S. facility and consists of a field of 271 flat mirrors 1 meter in diameter arrayed in a hexagonal pattern. The mirrors direct the incident solar radiation into a downward facing, cylindrical, cavity type boiler-superheater 1 meter in diameter suspended about 9 meters above the center of the mirror field. The flat mirrors which act as heliostats in this facility are each supported on a specially designed mechanical mount called a "kinematic motion." All of the kinematic motions are mechanically linked together through a common drive shaft so that they move together by a central clock drive mechanism. This mechanism controls the motion of all of the flat mirrors so that they follow the sun through the day and keep the incident solar radiation directed into the boiler-superheater. This system has produced steam at the rate of 150 kg/hr at 150 atmospheres and 500°C with an incident insolation of 900 W/m<sup>2</sup> giving an overall thermal efficiency of 70 percent (ref. 18).

#### i. Air Force Applications

Of the two basic solar thermal conversion system concepts, only the total energy system shows promise for Air Force application. The central receiver system is primarily for large scale power production, and it is not envisioned that the Air Force will ever become a major electrical power producer. The total energy system, on the other hand, provides both electrical and space conditioning needs for a single facility or a cluster of facilities. One of the major problems anticipated is the energy consumption and demand characteristics

of most facilities which are only operated 8 hours a day. Ideally, one or more facilities should have a nighttime utilization and corresponding energy demand. A solar thermal conversion system located on or adjacent to a fairly large facility and furnishing energy to that facility as well as a few military family housing units would satisfy this requirement. Remote or isolated sites might also prove to be excellent candidates for such a system.

Solar thermal conversion systems will not reach significant installed capacity until 1990 to 2000; and this will be limited exclusively to the Southwestern United States. Figure 10 shows the general area of the U.S. which will be affected by solar thermal conversion systems, as well as that area which is most conducive to system location.

#### 4. PHOTOVOLTAIC ELECTRIC POWER SYSTEMS (PEPS)

The development of solar photovoltaic conversion systems for terrestrial applications has many advantages as well as the potential to make a tremendous contribution to the nations energy needs. Major advantages include modular design of photovoltaic arrays to allow replacements of and additions to systems without incurring downtime of the entire power plant; the utilization of existing structures; dual use of lands for PEPS and other functions; simple operation and maintenance; and most important, the ability of PEPS to convert sunlight directly into electricity. Another important aspect is that of all solar energy systems presently under development, PEPS are least affected by "economics-of-scale," so that distributed systems on the roofs of individual facilities and residences are anticipated to show early economic feasibility. Another distinct advantage of PEPS over solar thermal conversion systems is its inherent ability to utilize both beam and diffuse radiation (ref. 11).

The major barrier to PEPS is cost. Present costs are astronomical due to the lack of a transitional market between the present high cost arrays and the required low cost arrays for terrestrial power applications. Another important fact is that the demand to solar cell arrays for use in the space program has been characterized by the requirement for high efficiency and low weight, with basically no constraints on array costs.

Major developments necessary for economically viable photovoltaic electric power systems to be used by 1985 include the production of low cost polycrystalline silicon material, achievement of a continuous growth process for the practical production of single crystal silicon, and development of automated

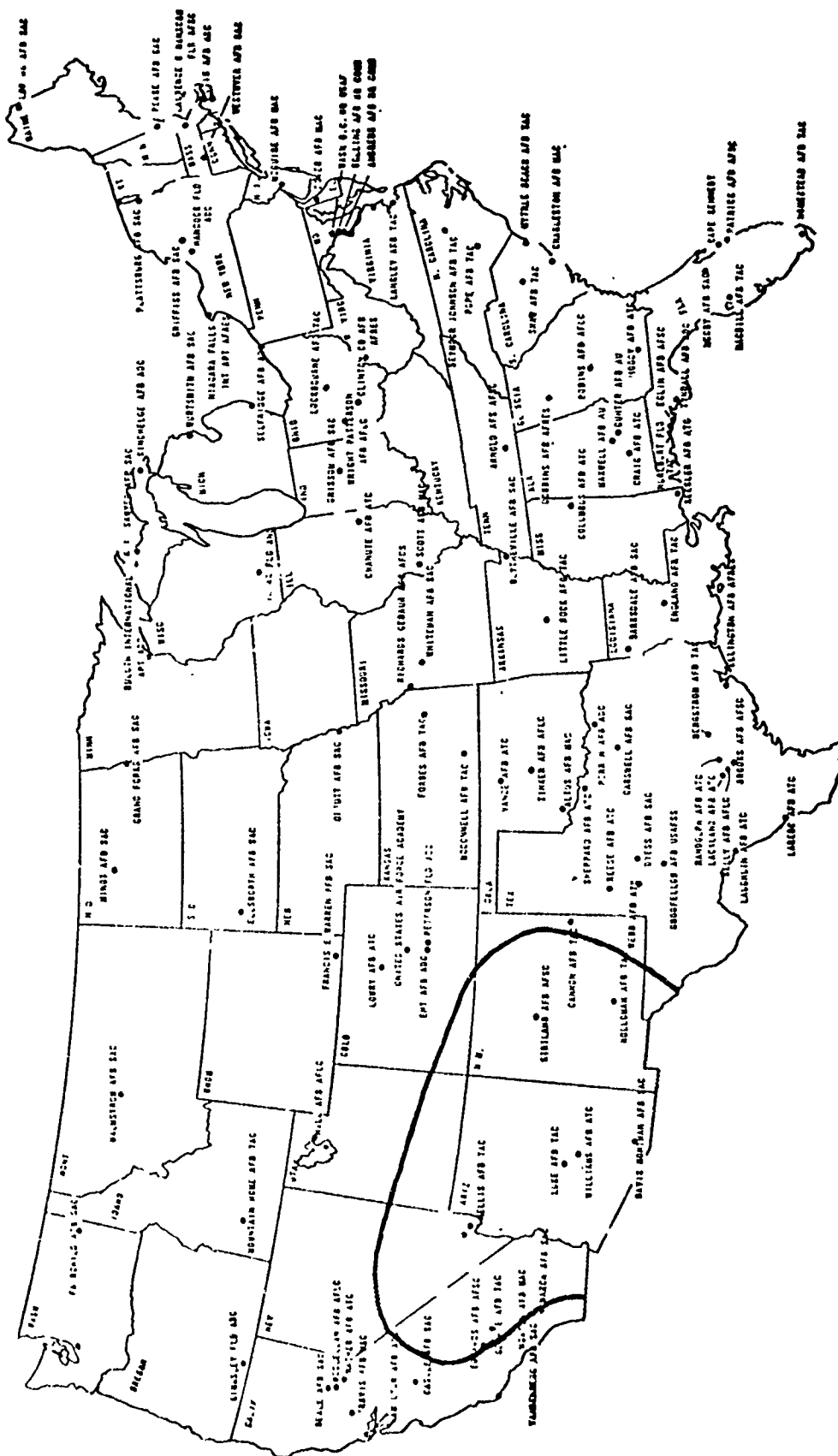


Figure 10. Potential Solar Thermal Electrical Conversion System Region. This figure is merely intended to show the general geographical area which possesses good potential for solar thermal systems. Other locations may exhibit potential upon further analysis of the direct normal radiation component when tilting and/or tracking is taken into consideration.

production techniques for processing single crystal silicon into completed photovoltaic arrays. Although major emphasis has been placed on silicon cells, thin films primarily of cadmium sulfide, cadmium telluride, and gallium arsenide have been studied and will be subjected to a screening process to select the candidates which merit further development (ref. 11).

Possible options for PEPS utilization are shown in figure 11. This figure represents a rather large overview and includes energy collection, conversion, storage, transmission and distribution, and utilization. The photovoltaic cells convert collected sunlight to DC electricity, which is then used directly or further converted to either AC electricity or to hydrogen gas. The hydrogen can be converted to methane, methanol, ammonia, etc., by gas treatment units. These various fuels can be stored for future use in many ways. Short term storage can be accomplished by means of batteries, flywheels, pumped storage, tanks, etc.; whereas, long term storage includes the storage of compressed air or hydrogen gas in depleted natural gas wells. Possible means for transmission and distribution, and utilization are also shown in figure 11.

#### a. Air Force Utilization of PEPS

Photovoltaic electric power systems can and most likely will have a tremendous effect on USAF installations throughout the world. PEPS costs should be very competitive with fossil fuel costs by 1990, and the Air Force should move into user status in the 1990 to 2000 time frame. Dispersed systems for individual facilities or even small clusters show excellent possibility for administrative/operation sections of bases, and central systems for housing areas also show potential. The most promising mode of operation of photovoltaic devices for central station application appears to be to deliver intermediate or load-following power to the total electrical grid. Such utilization would require mutual agreements with local utility companies and could easily prove to be beneficial to both parties. Problems would include the optimum mix of storage and conventional back-up capability and the requirement for both capacity and energy displacement capability if the system is integrated into utility power grid. Storage capabilities must be closely analyzed along with plant capacity factors for base-load, intermediate, and peaking applications.

A potential problem area which must be discussed is the difficulties associated with interfacing with utilities for dispersed application of PEPS. In this instance, the utility company is only called upon to deliver power in

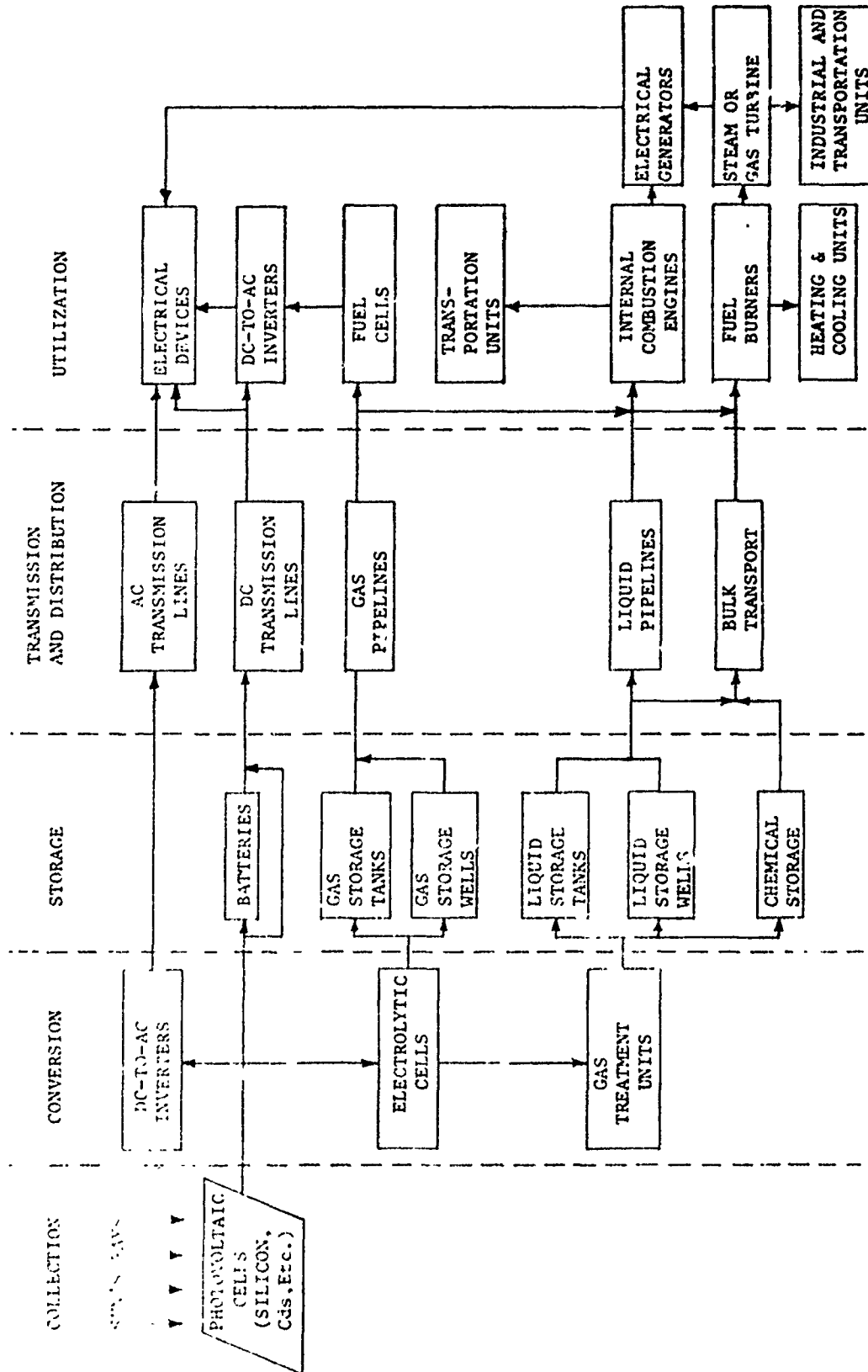


Figure 11. Optional PEPS Fuel Cycles (Ref. 11)



case of outages. This is obviously unattractive to the utility, since the required generation capacity must be built to supply the occasional back-up power, thus requiring large capital outlays and providing low revenues. To supply this back-up power, the utility companies are forced to either charge astronomical rates for the back-up power or simply refuse to provide back-up service at all. For an Air Force installation this might not be such an ominous problem, depending on whether the base had a central station plant as well as dispersed application, and on the base's general requirements of conventionally supplied power. The general key to successful dispersed applications is through the achievement of diversity of load and minimizing the peaking of the electric power demand.

## 5. COMBINED THERMAL-PHOTOVOLTAIC SYSTEMS

Another concept which has potential is the combined thermal-photovoltaic system. The University of Delaware has constructed a house to obtain data and demonstrate that solar energy can substantially contribute to the energy requirements of a house and to conserve energy by shifting the main use of auxiliary electric power into off-peak hours. The house (Solar One) combines limited solar-photovoltaic electrical power generation and solar thermal space conditioning. One of the major goals of the project is to demonstrate incentive to power utility companies to support such dispersed applications. These incentives may be provided by peak shaving as shown in figure 12. This figure shows a typical power demand curve (1) for an average summer day in Delaware and a possible solar electric harvesting of 50,000 one family houses with collector surfaces similar to Solar ONE (2). With only minor storage (4), almost complete peak shaving (5) may be achievable. Additional use of space conditioning equipment during night hours could fill-in the night demand valley (6). Curve (4) may be accomplished by radio-controlled load switching initiated by power utilities according to the experienced power demand (ref. 19).

Another feature of the system is its power-on-demand capability to provide load relief in case of a power emergency. Specifically, the battery will not be depleted below a certain stand-by reserve for its day to day operation. This reserve would be available to the user in an emergency, and this method of operation provides a longer battery life as well as a higher degree of reliability and safety of this combined solar plus auxiliary system. The system will eventually provide 80 percent of its total energy demand from solar input with the remainder supplied from the power utility (ref. 19).

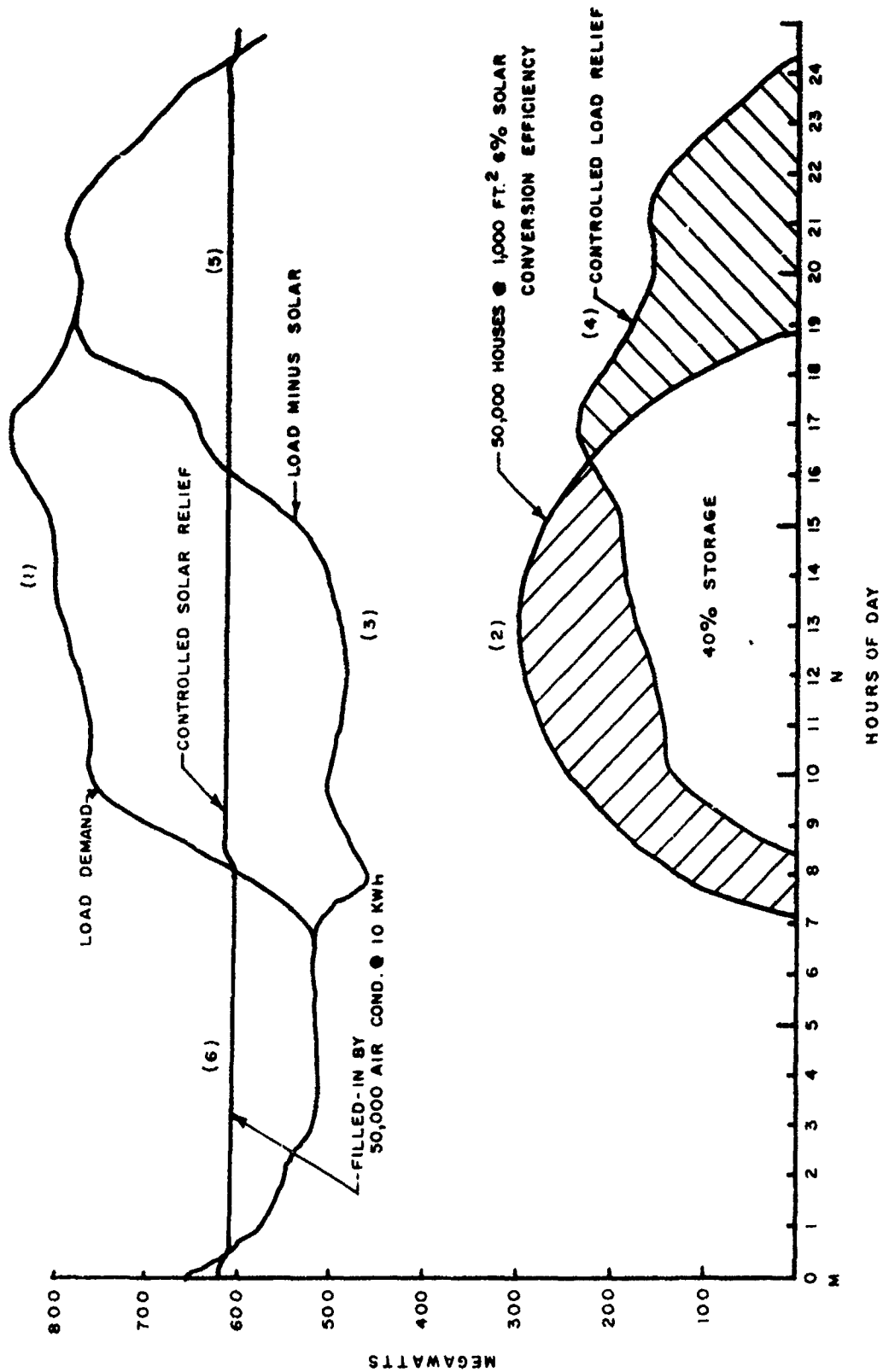


Figure 12. Example of Peak Shaving Utilizing Distributed Solar Conversion Systems (ref. 19)

## SECTION V

### WIND ENERGY

#### 1. INTRODUCTION

Until the 20th century, wind served an important part in our civilization. It drove ships and the windmills which ground the grain, pumped the water, and even generated some of the electricity. The discovery of oil, the invention of the steam and internal combustion engines, and large scale implementation of central power plants and transmission systems were all responsible for the rapid decline in the use of wind as a power source, so that today the wind is only used in those isolated areas where conventional forms of energy are too expensive (ref. 20).

The windmill improved slowly through the centuries with the most significant improvements in size, power output, and efficiency occurring in the late 1800's and through the 1930's. This was a result of the increasing capability in aerodynamics, electrical power generation, and structural design. The USA, the Soviet Union, Germany, England, France, Denmark, and others devoted much attention to developing large scale wind driven generators in the period from 1900 to 1950. Many systems were constructed and successfully operated, but none could compete with the cost of conventional fuels. It appears that there was no motivation to develop cost effective wind turbines due to the abundance and low cost fossil fuels, as well as the uncertainty of the wind in meeting energy demands. For these reasons the work in developing large scale wind turbines diminished, so that very little effort indeed was put forth on wind energy (ref. 20).

The energy crisis and soaring costs of conventional fuels have rekindled interest in alternative energy sources such as wind, and ERDA and NASA have taken the lead role in implementing programs to develop economic wind energy systems.

#### 2. HISTORY

Denmark, lacking fossil fuel and hydroelectric energy sources, was the first nation to generate electricity from the wind. The Danes developed a rotor wind generator 75 feet (23m) in diameter in 1890, and by 1910, a few hundred wind

turbines ranging in capacity from 5 to 25 kW were in operation. The total installed capacity was 200 megawatt hours (electric)(MWHe) with total generation at  $5 \times 10^5$  MWHe/year (ref. 21).

The windmill played an important part in the development of the western United States with an estimated 6.5 million units constructed during the period 1880 to 1930. Most of these units were used for pumping water and running saw-mills, but some were used for the generation of electricity. Even as recent as 1950, there were about 50,000 small wind generators, the most common models being the Wincharger (200 to 1200 kW) and Jacobs (1.5 to 4 kW). In 1954, Russia is estimated to have had 29,500 wind power plants with a total output of 125,000 kW (ref. 21).

The decline of the wind generators in this country from 1940 to 1970 was simply due to the availability of cheap fossil fuel and hydroelectrical energy to isolated areas. The supplying of low-cost electrical power to rural areas by REA and TVA was a major factor in the wind generator's demise.

The largest wind generator ever constructed was the Smith-Putnam unit. This unit consisted of a two-bladed, variable-pitch propeller, which had a blade diameter of 175 feet (53m), and was mounted on a 110-foot (34m) tower on Grandpa's Knob, Vermont. The weight of each steel blade was approximately 8 tons. A 1.25 MW generator was coupled to the AC power grid of the Central Vermont Public Service Corporation, and the unit was phased-in to the grid on 19 October 1941. This represented the first synchronous generation of power from the wind, and during the next 4 years, the Smith-Putnam wind generator operated intermittently for about 1100 hours. The system demonstrated the technical feasibility of extracting power from the wind on a large scale, with the cost of generated power about 50 percent greater than the inexpensive hydroelectric power in Vermont. The unit was closed down due to fatigue induced failure of a stainless steel blade, and this was possibly a result of the poor quality of wartime materials (ref. 21).

Oregon State University has performed a study to estimate the cost of the Smith-Putnam wind turbines if constructed in 1971. Assuming that the production run of these generators consisted of 100 units of the 1500 kW size, the total installed unit cost was estimated to be \$1,051,000. The associated cost per installed kilowatt would be \$700. It was also estimated that if the wind turbine was installed in a better location such as Lincoln Ridge in Vermont,

where the annual wind velocity at the windmill hub is 25 mph (17 mph at Grandpa's Knob), the annual output would be 3500 kilowatt-hours/installed kilowatt-year. Assuming a lifetime of 20 years, the output of one unit throughout its life would be 70,000 kilowatt-hours/installed kilowatt. This would in turn lower the cost per kilowatt hour of electricity to \$0.010 per kW (ref. 22).

Today, the United States is still behind many nations in wind energy conversion technology. The most advanced small systems are produced in France, Switzerland, and Australia. The Russians apparently have large numbers of 30 kWe units in operation in remote areas including the Russian Arctic territories; and there is indication that they have larger systems than this in operation. The largest known existing system is a 70 kWe experimental unit recently constructed in Germany (ref. 11).

### 3. PRESENT UNITED STATES WIND ENERGY CONVERSION PROGRAM (REF. 21)

The specific five-year objectives of the Wind Energy Conversion program are to:

- a. Operate and evaluate 100 kWe wind energy systems at selected sites and improve units at user sites;
- b. Utilize operational data obtained on 100 kWe-scale systems for application to future MWe-scale systems;
- c. Design, construct, operate and evaluate MWe-scale single and multi-unit wind energy systems;
- d. Operate and evaluate MWe scale second generation advanced systems in a user environment;
- e. Complete the preliminary design of a 100 MWe system;
- f. Complete the system analysis and assessment of a future offshore hydrogen producing system;
- g. Operate and evaluate a series of systems in a farm environment; and
- h. Assess wind resource data over the United States.

The ERDA exploratory 100 kWe wind generator system previously designed and now under construction at the NASA Lewis Research Center will be used to evaluate components and subsystems such as composite rotor blades, low-cost hub and pitch-change mechanisms, field-modulated generators, and storage systems.

Development and construction of large-scale wind energy systems will be initiated for test in user environments. A detailed design will be developed for a 100 kWe wind system utilizing the experience gained at the NASA Lewis

Research Center. The system will be designed for cost minimization rather than as a research tool and will be developed to supply power directly to users requiring moderate capacity power production. Construction will commence in FY 1976 on three such systems to be installed in three different climatic areas. These systems will provide operating, performance, and economic data regarding wind systems operating in a user environment and supplementing other sources of power.

Detailed design will be completed and construction started on a 1 MWe-scale experimental system. This system will be used to supply electrical power to the grid of a utility system and is the type of system contemplated for use in supplying large-scale power from wind energy systems.

Wind surveys and site selection procedures started in FY 1975 will be completed in FY 1976.

#### 4. WIND ENERGY POTENTIAL

Wind energy varies by gusting and other short time-span patterns and follows diurnal, seasonal, and yearly patterns. It is also a function of weather geography and topography. The average amount of wind energy in the first few hundred feet of altitude across the United States and its territories represents an enormous quantity of energy. A vertical square meter of area contains, on the average, approximately the same power density as a horizontal square meter receives in direct solar insolation--250 watts per square meter. The actual amount of energy that can be extracted from the wind is dependent upon allowable spacing of and number of wind turbines in those regions having fairly high average wind profiles. The most attractive regions for wind systems appear to be the Great Plains area east of the Rocky Mountains and extending from Texas to Montana, as well as Alaska, New England, the Great Lakes, the Pacific Coast, Hawaii, and most island areas. Table 18 shows the estimated wind energy potential by the year 2000 for a few of the better regions. This estimated annual power production of  $1.5 \times 10^9$  MWe per year represents almost 80 percent of the present United States demand for electricity (ref. 11).

#### 5. DEVELOPMENT PROBLEMS

Although there are no critical technical feasibility problems precluding the use of wind energy conversion systems (WECS), there are problems and uncertainties associated with manufacturing costs; operational capabilities, and climatology. Problem areas include (ref. 11):

Table 18

## ESTIMATED ELECTRICAL ENERGY PRODUCTION FROM WIND POWER (REF. 11)

Site	Annual Power Production Times $10^9$ kWh
Offshore, New England	318
Offshore, Eastern Seaboard	283
Offshore, Texas Gulf Coast	190
Great Lakes	133
Great Plains	210
Aleutian Chain	402
Total	1536

a. Maintenance and operating costs are projected to be low and, indeed, have traditionally been low. These costs must be verified and will depend strongly upon such factors as the yet unknown operating lifetimes of blades.

b. The overall wind potential of the United States and the potential and character-of particular regions need to be better defined.

c. Knowledge of low altitude wind characteristics is inadequate, and the ability to identify and verify the wind characteristics and to accurately predict these characteristics at particular sites, in a timely, inexpensive and reliable manner, is not satisfactory. The delivered power price in mills/kWh, is very sensitive to this problem. In addition, blade loading and life are a direct function of local windgust characteristics. At the present time, only a limited data of this nature are available on which to base gust-load estimate.

d. The requirements for energy storage for particular applications, as a function of energy demand and wind availability and the associated system costs as a function of application, are not yet defined. Many applications may be considered, including the use of a WECS network as a means of reducing storage requirements by special averaging of wind variations, or the use of wind energy solely as a fuel and water saver, or consideration of wind systems as firm-power, including full storage requirements.

e. Legal questions on ownership of rights to wind energy (analogous to water rights) have little precedent.

f. WECS environmental effects and inadvertant weather modification, on both large and small scales, are believed to be insignificant, but research may be required to verify that estimate, as well as to examine other possible impacts associated with eventual large scale use. Possible TV rception interference by rotating blades requires examination.

g. Uncertain reaction of the public to aesthetics and of industry to the unusual and seemingly "quaint" nature of the system.

h. The dynamic characteristics of the wind generator system must be studied to prevent operation in a potentially self-destructive manner. Although the helicopter industry has provided much experience on this problem, the wind generator operates in a sufficiently different range of parameters that considerable study will be required to ensure a sound dynamic design. Past experience with both wind machines and helicopters has shown that dynamic behavior also has a direct influence on rotor life.

## 6. STORAGE

The main disadvantage of wind power is its intermittant nature. This can be overcome by standby plants using conventional fuels or by developing efficient and economical energy storage techniques. It is somewhat difficult to discuss energy storage systems since it is not always required, and when it is, the actual requirements are not clearly defined. It is important to be aware of this as well as being aware that energy storage costs cannot realistically be tied into wind generated power costs since they are independent of each other.

As mentioned in the preceding paragraph, there are those wind energy applications which do not require energy storage. On-line generation of wind power is a good example with many engineers advocating the feasibility of simply feeding wind generated power into the grid as it is produced. This of course, would require frequency controlled alternators for example, and research and development is underway to reduce weight, size, and costs of such alternators. Others have advocated direct-nonsynchronous machines in which AC is converted to DC and back to AC again utilizing batteries as the intermediate DC step. This method has the advantage of decoupling the variable frequency source, the wind turbine, from the fixed frequency load. This procedure has been used successfully for large scale plants but would require further development for small scale applications (ref. 20).



### a. Battery Storage

There are numerous energy storage systems and a short discussion of each is necessary. Batteries are the most familiar form of energy storage. The use of batteries is attractive because they are simple devices which require no complex facilities and little repair or maintenance during their operating life. Batteries can be packaged and modularized and are totally free of the geographic constraints found in other proposed storage systems. In addition, they produce no harmful emissions and are available on an almost instantaneous basis. The major problem with battery systems is cost. Costs are primarily determined by life and the size (or quantity of energy to be stored). The size is fixed by the required power and the maximum length of windless period during which the battery is to operate (ref. 24). The life is affected by number of operating cycles, the rate of battery charge and discharge, and the percentage of total stored energy withdrawn in a cycle.

Basically, there are three classes of batteries which are considered for bulk energy storage: (1) conventional, (2) metal-gas, and (3) high-energy-density alkali-metal types. Table 19 summarizes the characteristics of these batteries. Column headings include energy density, which measures the size of the battery required to store a given amount of energy; power density, which measures the batteries ability to deliver high current; and life cycle, which is simply the number of charge-discharge cycles (ref. 24).

In summary, the standard lead-acid battery is a rather mature technology, and there is subsequently only a modest opportunity for cost and performance improvements. The most promising R & D opportunities appear to be in other advanced battery systems. There is a very real possibility that critical material shortages may result, particularly if lead and zinc are to be used extensively. Another major consideration is the question of whether battery bulk energy systems will have heat dissipation problems with corresponding thermal pollution (ref. 24).

### b. Electrolysis of Water/Hydrogen Storage

The electrolysis of water with storage of energy in the form of hydrogen offers excellent potential for wind energy conversion systems. The use of hydrogen as a primary fuel will require the development of a large scale transmission and storage system. A hydrogen gas pipeline capable of delivering the gas directly from the generating plant to the users appears to be most desirable. Problems

Table 19  
BATTERIES FOR BULK ENERGY STORAGE (REF. 24)

Type of Battery	Energy Density (watt-hours/lb)	Power Density (watts/lb)	Cycle Life (charge- discharge cycles)	Major Problems
I. Conventional Batteries				
A. Lead-Acid	10	20 to 30	1500	Gassing, Maintenance, Efficiency Life
B. Nickel-Iron	25	50	?	
C. Nickel-Zinc	30	150	200 to 400	
II. Metal-Gas Batteries				
A. Iron-Air	40 to 50	10 to 20	---	Cathode Corrosion, Life Life, Cost Volume, Life Life, Cost Life, Cost Life
B. Zinc-Air	40 to 50	10 to 20	---	
C. Nickel-Hydrogen	30 to 40	?	---	
D. Zinc-Oxygen	50 to 60	10 to 30	---	
E. Cadmium -Oxygen	30 to 40	40 to 60	---	
F. Zinc-Chlorine	50 to 75	40 to 60	---	
III. Alkali-Metal High-Temperature Batteries				
A. Sodium-Sulfur (Beta (Beta Alumina))	80 to 100	80 to 100	200 to 2000	Life, Cost
B. Sodium-Sulfur (Gas)	80 to 100	80 to 400	100+	Life, Material Stability Materials, Corrosion, Cost Life
C. Lithium-Sulfur	100	100	2000	
D. Lithium-Chlorine	50	100	100	

associated with such a pipeline include leakage, safety, economics, and hydrogen environment embrittlement of pipeline materials. It will be necessary to provide storage for daily and seasonal peak shaving requirements as well as for periods when the wind is inadequate for power generation. Daily needs can be taken care of by line pack storage. Seasonal peak shaving and calm period requirements may be economically satisfied by large scale underground storage in depleted natural gas fields, aquifers, or other such natural formations. More costly methods of storage include high pressure tanks, liquid hydrogen, and gas storage in mined caverns (ref. 25).

The hydrogen liquefaction is expensive in spite of a fairly well developed technology. The major reasons for the expense are that the process requires a large amount of energy and the process requires complex equipment. The storage of the liquid hydrogen adds even greater expense as a result of cryogenic properties and associated storage problems. It is apparent that hydrogen will only be transported and stored as a liquid when there are no alternatives--an example being the storage of energy for peak-shaving in a large power system where suitable gas storage facilities are not available (ref. 25).

Hydrides have certain useful and advantageous properties in comparison to gaseous and liquid hydrogen, with the primary one being volume energy density. Also, even though the gas is stored at densities greater than liquid hydrogen, there are no liquefaction and cryogenic storage problems associated with hydride useage. Unfortunately, hydrides have very poor mass energy densities and the costs of the metals would be prohibitive. Therefore, it appears that hydride storage will be limited to small scale specific uses rather than large scale applications (ref. 25).

Summarizing, it appears that there are no technological or economical barriers to the transmission and storage of hydrogen either as a gas or liquid in a hydrogen economy. Social, environmental, and safety costs will probably create no greater problem than natural gas transmission and storage systems did a few years ago.

#### c Pumped Water Storage

Pumped water storage systems are basic and do not require further R & D since it is an established procedure. Costs are fairly well established with a figure of \$180 per kilowatt-hour (electric) being considered as average. The

system's efficiency is competitive and rated at 67 percent. The major drawback of pumped water storage is the limited number of acceptable sites available. Climate, geology, and geomorphology determine the adequacy of potential storage sites, but unfortunately, the most acceptable areas are often far removed from load centers and are environmentally undesirable because they occupy large areas of land (ref. 26).

#### d. Compressed Air Storage

Compressed air storage represents another possibility and is attractive to large scale wind turbine systems. In general, a compressed air storage system consists of three components: a compressor, a motor, and a turbine. To store the energy, a motor drives the compressor, and to extract the energy, the air is run through the turbine driving that same motor, which now acts as an alternator. The compressed air can be stored in tanks and underground caverns or aquifers. The use of caverns requires a water piston, a surface area, and a surface lake to recover flow-work, which is normally not recovered when pumping into an inflexible tank. Utilization of an aquifer to store the compressed air offers greater potential than the others, primarily because the water in the interstitial spaces acts as the piston and thus no surface area is required. The flexibility of underground storage of air is another important characteristic that must be discussed. In competitive storage systems, when the full storage capacity is reached, no further storage is possible, whereas with air, it is possible to simply continue compression. In the case of an aquifer, the air will be pushing the aquifer close to the dome with the piston action being obtained simply by the increased air compression. Again since air is a compressible fluid, a great amount of energy can be stored by increasing the pressure or by forcing back more of the interstitial water in the aquifer. Compressed air storage costs are estimated at about \$80 per kilowatt (refs. 26 and 27).

#### e. Flywheel Storage

Flywheel storage systems have been used in very few applications in the past, but modern technology has provided a tenfold improvement in flywheel systems since the turn of the century. The major disadvantages of flywheel systems have been the limited energy storage capability (about one-tenth of that of a lead-acid battery), the poor energy storage efficiency (short rundown time), and the danger of catastrophic failure. Higher performance flywheels have increased energy storage efficiency but at the same time have increased the hazard

of catastrophic failure. This is due to the increase in energy of the failed pieces (ref. 28).

The Applied Physics Laboratory has been studying a new superflywheel concept that appears to offer greatly improved safety, as well as performing better than the best optimized steel flywheel. The configuration of the flywheel appears to make effective failure containment a practical objective. The development of this superflywheel storage system will contribute greatly to future on-site energy system performance. Advantages of the superflywheel system include lower total cost, long operating life, and capability to accept high-power peaks associated with heating and air conditioning equipment (ref. 28).

There are presently 10 different materials that appear to offer more economical storage than the conventional lead-acid battery. Glass, fiber glass, DuPont fiber-B and PRD-49, and music wire represent the most common materials. It is therefore possible that a successful superflywheel development could provide an energy storage system with the economy of a lead-acid battery but without any of its limitations, such as maintenance, depth of discharge, low power peak capability, cycles to failure, emissions, and DC to AC conversion (ref. 28).

A wind power system with superflywheel storage has the potential to be more efficient than any other known energy storage concept. This is primarily due to the fact that the wind turbine energy can be transmitted directly to the flywheel through gears and shafting at very high efficiency. The flywheel can then be connected directly to the AC generator without the need for gearing.

## 7. WIND TURBINES

There are two basic types of wind turbines--horizontal axis and vertical axis. The horizontal axis approach is the most common and consists of blades or vanes rotating about a horizontal axis with the plane of the blades essentially perpendicular to the wind velocity vector. This system has been improved over the years and has received substantial attention, perhaps largely due to the availability and advance of propeller theory. The vertical-axis approach was developed in the 1920's, with the Darrieus rotor being developed in 1925 and the Savonius rotor in 1929. Although a number of applications were developed for the vertical-axis rotor, the concept never became popular. Interest was renewed in the Darrieus type wind turbine when the National Aeronautical Establishment of the

National Research Council of Canada independently developed a similar wind turbine in 1971.

The Savonius rotor basically operates as a two stage turbine wherein the wind impinging on the concave side is circulated through the center of the rotor to the back of the convex side, thus decreasing what might otherwise be a high negative pressure region. This rotor has been applied to water pumps, ship propulsion, and building ventilators--all with some success. Savonius also showed the feasibility of using the energy in ocean waves to drive the rotor which led to the development of a present ocean current meter (ref. 29).

The operational principle of the vertical-axis wind turbine is analagous to the aerodynamics of an airfoil. As a fluid flows over an airfoil, two forces are exerted on the section--the drag force, parallel to the wind, and the lift force which is perpendicular to the drag force. Figure 13 shows a symmetric airfoil in which the chord line represents the centerline of the cross section. The angle of attack ( $\alpha$ ) is the angle between the chord line and the wind direction ( $W$ ). As is true with most airfoils, the lift to drag ratio ( $L/D$ ) increases with increasing angle of attack until stall (flow separates from the airfoil). The Darrieus vertical-axis wind turbine (figure 14) presents a somewhat different problem since it has rotating airfoils. First of all, as shown in figure 13, the velocity of the wind relative to the blade is the absolute blade velocity,  $R\omega$ , subtracted from the absolute wind velocity,  $V$ . The angle of attack for a rotating airfoil is the angle between the relative wind speed, ( $W$ ) and the chord line. Again referring to figure 13, the angle of attack, ( $\alpha$ ) is dependent on the wind speed ( $V$ ), the rotational speed ( $R\omega$ ), and the blade position angle ( $\theta$ ). The actual rotational forces are determined by projecting the lift force ( $L$ ) and the drag force ( $D$ ) onto the direction of the chord line of the airfoil. Rotation in a counterclockwise sense is caused by the chordwise component of the lift forces, whereas the chordwise component of the drag force opposes this motion. The driving torque will always be positive as long as the chordwise lift force is greater than the chordwise drag force (ref. 30).

The Darrieus wind turbine offers the following advantages relative to the more conventional propeller wind turbines (ref. 31).

- a. Vertical symmetry eliminates need for yaw control and can accept wind from any direction.

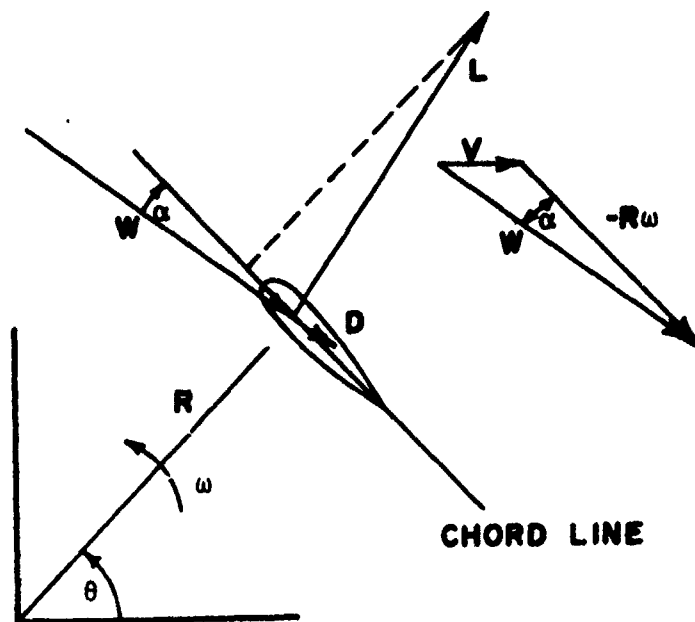


Figure 13. Aerodynamic Forces Acting on a Rotating Airfoil (ref. 30)

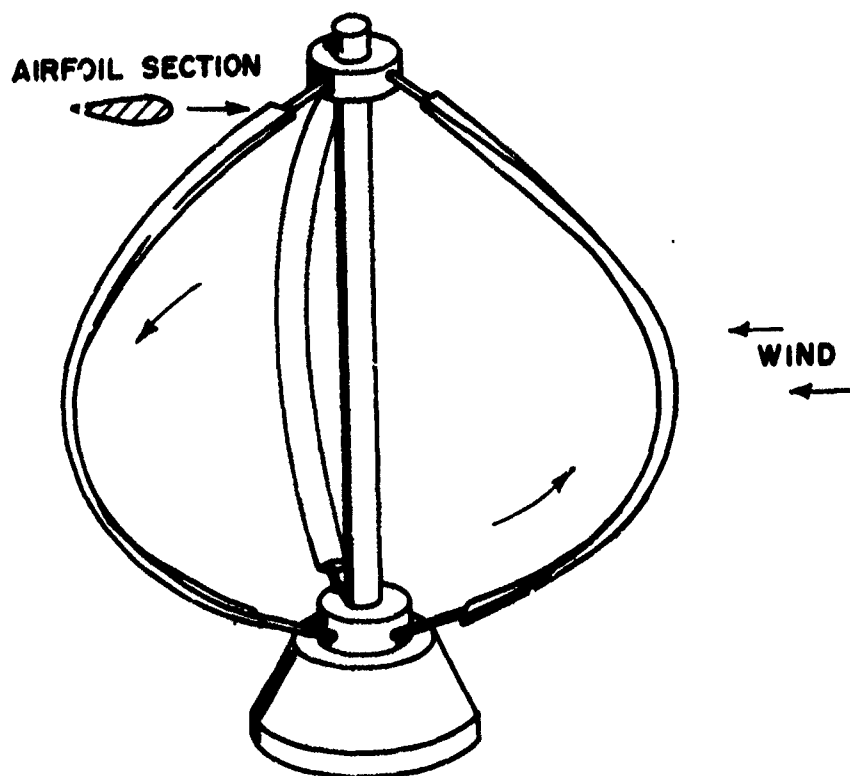


Figure 14. Vertical Axis Wind Turbine (ref. 21)

b. The generator can be placed on the ground level, without costly bevel gearing and will therefore provide less weight aloft, simpler tower construction, and cheaper maintenance.

c. Lower fabrication costs because of simple tower construction (guy-wired pedestal), less structure/swept area, and reduced blade fabrication costs (no twist or taper).

d. Easier to scale-up structurally.

e. Capable of operation in higher winds.

An additional advantage may involve the direct driving of synchronous generators by wind turbines in parallel operation with a synchronizing electrical power network. It has been shown that, with proper generator sizing, torque regulating devices need not be provided on the turbine as a result of the aerodynamic characteristics of the Darrieus rotor. It must be point out, however, that although torque regulating mechanisms are usually considered for propeller-type turbines to prevent exceeding the generator's pull-out torque rating, it may also be possible to design the necessary aerodynamic characteristics into a propeller-type turbine to prevent this pull-out (ref. 32).

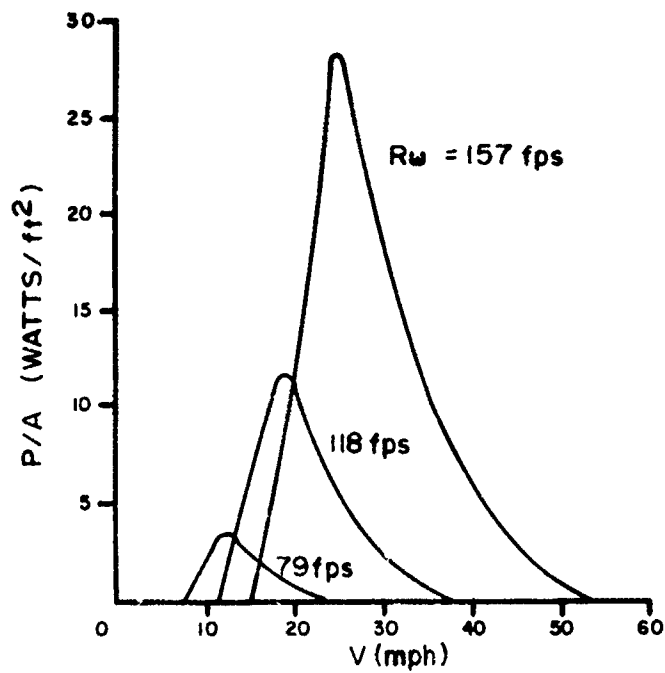
The relationship of interest for synchronous wind turbine power generation is that of turbine power to wind speed for a fixed rotational speed. When turbine power per unit swept area is given as a function of wind speed, this self-regulating characteristic can be shown graphically. Figure 15 shows this relationship with the tip speed as a parameter (ref. 33). Upon selection of a tip speed, it is apparent that for some wind speed there is a maximum power per unit swept area which will not be exceeded at any other wind speed. Therefore, if the rate power of the generator is specified to correspond to this maximum, the generator pull-out torque rating will not be exceeded, and no torque regulating mechanisms will be required on the turbine (ref. 33).

It is apparent that additional investigation and development is required before it can be stated that a vertical-axis wind turbine is better than a horizontal-axis wind turbine or vice versa and that relative cost-efficiency comparisons are essential for analysis of any application.

## 8. POTENTIAL OF WIND POWER FOR AIR FORCE INSTALLATIONS

The first step in determining wind power potential is to address the actual calculation of wind power. It is determined from the kinetic energy of the wind per unit of time.





$$P/A = \frac{1}{2} \rho V^3 C_p \frac{R\omega}{V}$$

where , ,

- P/A - power per unit swept area
- $\rho$  - air flow density
- V - wind speed
- $C_p$  - power coefficient
- R $\omega$  - tip speed

Figure 15. Turbine Shaft Power for Synchronous Operation (ref. 33)

$$P = \frac{KE}{t} = \frac{mV^2}{2t} = \frac{1}{2} \dot{m}V^2 = \frac{1}{2} \rho AV^3$$

Where

KE - kinetic energy

t = time

m = mass

$\dot{m}$  = mass flow rate

V = wind speed

$\rho$  = air density

A = cross sectional area perpendicular to flow

The cubic response of power to wind speed requires use of a climatological frequency distribution of wind speeds for calculating wind power. If average wind speed data are used, the potential power may be less than half the power utilizing a frequency distribution. Table 20 shows this disparity.

Table 20

COMPARISON OF POTENTIAL WIND POWER USING FREQUENCY DISTRIBUTION  
VERSUS USING AVERAGE WIND SPEED

Installation	Power/Area (w/m <sup>2</sup> )	
	w/Distribution	w/Average Speed
Altus	114	43
F. E. Warren	303	137
McConnell	222	108
Shemya	660	330

It is important to point out that there are other factors which affect the accuracy of wind power calculations. Anemometer height and location in relation to other facilities, ground cover and other objects which alter surface friction characteristics, the geostrophic winds or the free air flow above the boundary layer, all contribute to possible inaccuracies in estimating wind power potential. For the basic comparisons and analysis in this report, data were accepted as contained in the Percentage Frequency of Wind Direction and Speed Tables obtained from the Environmental Technical Applications Center (ETAC). It must be pointed

out that there are other methods for calculating general wind potential and that the method used in this report merely intends to show those general areas which show promise for wind energy conversion systems. The actual amount of power that can be extracted from the wind at any given location would require further analysis to include detailed study of wind variability, physical properties of wind turbine, aerodynamic efficiencies, cut-in and cut-out speeds, and full power ratings.

Wind power potential was calculated for 11 CONUS installations and 16 Alaskan sites, as shown in tables 21 and 22, respectively. The CONUS installations were chosen, based on a national wind power map prepared by Sandia Laboratories. Figure 16 is an extract from this map and shows general areas where wind power could be most useful (ref. 34). The installations analyzed in Alaska represent the major USAF sites located in that State.

The general rule for the practicality of wind power utilizing present state-of-the-art conversion systems requires an average annual wind speed greater than 8.5 knots (10 mph). However, as previously shown, the annual frequency distribution is much more representative than an annual mean wind speed. If the distribution is used, the annual potential wind power per unit area should be greater than 150 watts per square meter if the site is to be considered as a potential location for a wind energy conversion system. This is a general rule of thumb and can change greatly depending on the specific application, fuel costs, location, etc. Another item to be considered is whether there are local phenomena conducive for wind power systems, such as the funneling effects from canyons or mountainous areas where wind speeds are much higher. Such conditions will not be indicated in any wind data for the installation as a result of typical anemometer location.

The annual march of wind power is shown graphically in figure 17 for four CONUS installation and in figure 18 for the Alaskan sites. It is readily apparent that the Alaska sites have exceptional potential for wind energy conversion systems. These sites represent outstanding candidates for demonstration systems. ERDA, NSF, and NASA are aware of the wind power potential at remote USAF sites in Alaska and it is imperative that the Air Force maintain interface with these agencies in carrying out the national program in support of Project Independence.

Table 21

## AVERAGE ANNUAL WIND POWER POTENTIAL OF SELECTED USAF CONUS INSTALLATIONS

Installation	Wind Power/ Wind Swept Area (W/m <sup>2</sup> )	Percent of Time (22-40 kt)	Percent of Time (22-40 kt)	Mean Wind Speed	Percent of Time Calm
Altus	114	53.5	1.7	8.0	10.9
Dyess	94	55.2	0.9	7.7	8.7
Ellsworth	267	54.4	8.0	9.9	11.2
F. E. Warren	303	70.0	9.0	11.8	0.6
Grand Forks	146	58.0	2.7	8.9	7.2
Malmstrom	169	55.7	4.4	8.9	10.9
McConnell	222	69.8	5.3	10.9	4.1
Minot	158	57.9	3.3	9.0	6.9
Reese	163	66.1	3.3	9.4	9.3
Sheppard	157	72.3	2.6	9.9	2.3
Tinker	265	68.8	8.0	11.4	4.1

Table 22

## AVERAGE ANNUAL WIND POWER POTENTIAL AT USAF ALASKAN SITES

Installation	Wind Power/ Wind Swept Area (W/m <sup>2</sup> )	Percent of Time (22-40 kt)	Percent of Time (22-40 kt)	Mean Wind Speed	Percent of Time Calm
Cape Lisburne	315	55.4	9.3	10.5	11.9
Cape Newenham	242	57.5	6.6	9.8	16.3
Cape Romanyof	355	57.8	12.3	11.7	12.2
Cold Bay	574	61.7	20.3	14.6	4.4
Eielson	16	13.3	0.1	2.7	45.0
Elmendorf	36	23.5	0.5	4.4	22.7
Fort Yukon	65	45.6	0.4	6.6	11.0
Galena	59	35.8	0.8	5.4	25.4
Indian Mountain	70	36.1	1.3	5.4	33.7
King Salmon	191	56.9	4.9	9.1	9.4
Kodiak	189	49.1	5.3	8.9	7.9
Kotzebue	292	61.5	9.2	11.1	3.0
Shemya	660	64.7	22.6	15.8	2.0
Sparravohn	64	30.8	1.2	4.7	41.1
Tatalina	31	28.1	0.1	4.3	32.2
Tin City	549	63.0	20.8	14.9	5.0

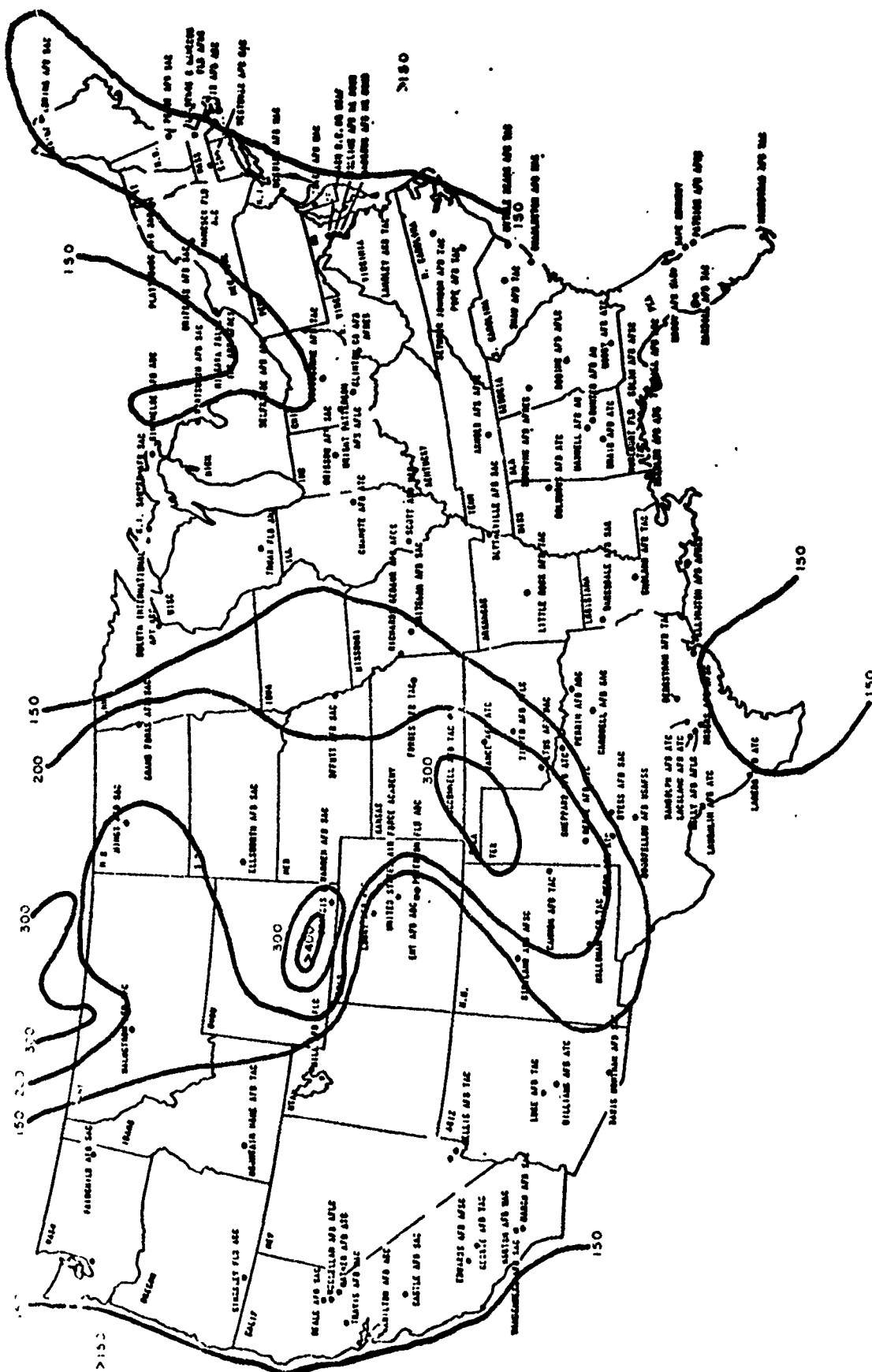


Figure 16. Map Showing Wind Power Potential (ref. 34). (Note: Only those areas having power potential greater than 150 watts/square meter are shown)

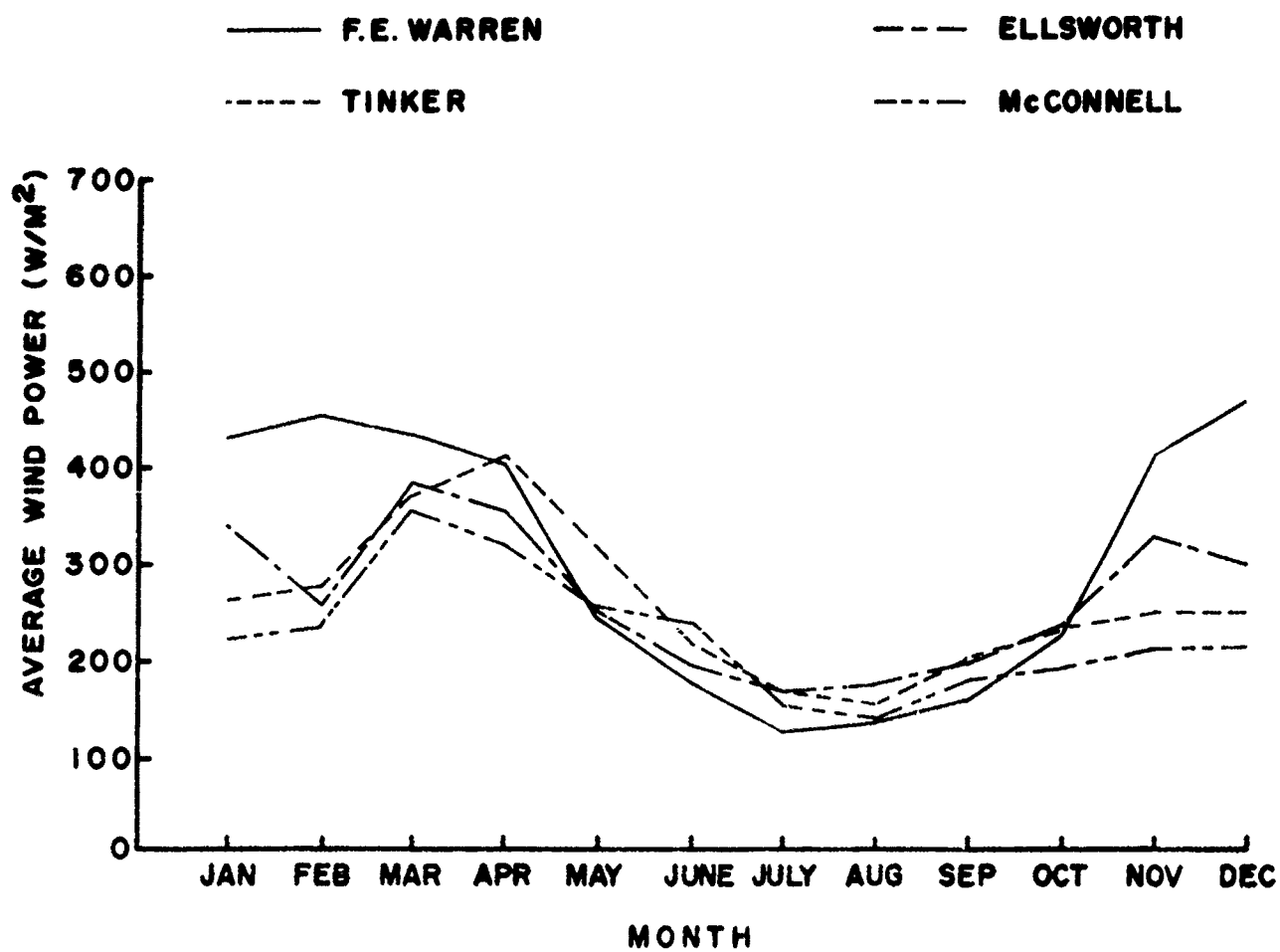


Figure 17. Annual March of Available Wind Power (Selected CONUS Sites)

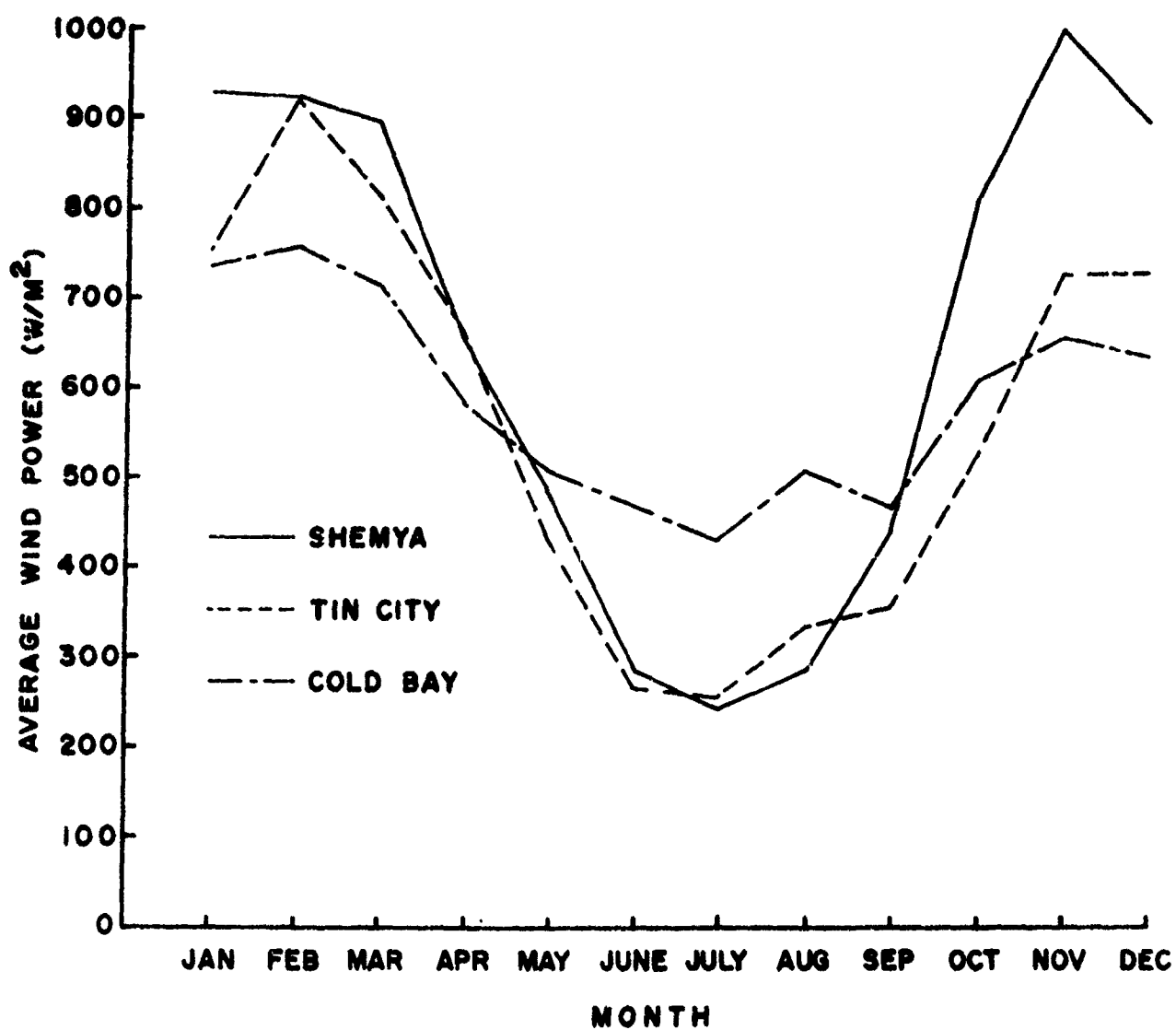


Figure 18. Annual March of Available Wind Power (Selected Alaskan Sites)



## SECTION VI

### GEOHERMAL ENERGY

#### 1. GENERAL

The earth's interior consists of rock at extremely high temperature, and this represents a reservoir of heat which exceeds foreseeable energy needs as well as the availability of fossil fuels located at the surface. There are of course no existing methods to completely utilize this heat for the world's needs. There are, however, certain geological processes in certain parts of the world which allow this molten rock to reach very close to the surface of the earth. Hot rock itself, is not conducive to a convenient and economical utilization of this heat, but where water exists as a heat transfer medium, the potential improves immensely (ref. 35).

The actual source of this internal heat is believed to be the natural decay of radioactive core material and frictional forces resulting from solar or lunar tides as well as the relative motion of crustal plates. The areas of greatest geothermal resources potential appear to lie along the tensional environments of the oceanic rises and continental rift systems, and along the compressional environments where mountains are rising and island arcs are forming (ref. 36).

Table 23 shows the potential of geothermal resources in the United States assuming funding and accomplishment of a comprehensive R & D program. The major question concerning this potential is what portion of the estimated geothermal resource base can actually be considered a viable resource. This depends on a number of factors, which include depth of extraction and temperature at that depth; effective porosity, specific yield, and permeability of the reservoir rocks; physical state of the fluid; technology; economics; environmental constraints; and Federal policy (ref. 37).

#### 2. RESOURCE CLASSIFICATION

Geothermal resources consist of the thermal energy and the fluids which are found in the earth and where the temperature of the formation and the fluids significantly exceeds that which is to be expected from normal vertical temperature gradients. Resource classifications and descriptions follow (ref. 37):

Table 23

## POTENTIAL OF GEOTHERMAL ENERGY RESOURCES (REF. 35)

	1975	1985	2000
Power (x 10 <sup>3</sup> MW)	0.75	132	395
Electrical Energy* (x 10 <sup>6</sup> MWh)	5.913	1,041	3,114
Oil Equivalent** (x 10 <sup>6</sup> bbl/day)	0.024	4.213	12.60
*90 percent load factor			
**3,412 BTU/kWh and 5,800,000 BTU/bbl of oil used at 40 percent conversion efficiency			

## a. Vapor Dominated Convective Hydrothermal Resources

These geothermal systems produce superheated steam with traces of other gases but little or no water. This characteristic permits piping of the entire fluid directly to the turbine. Experimental drilling has to date discovered five vapor-dominated systems. Only three of these offer commercial potential: Larderello, Italy; the Geysers, California; and Matsukawa, Japan. Another region in New Mexico, Valles Caldera, has only recently been discovered.

## b. Liquid Dominated Convective Hydrothermal Resources

These resources are convective systems, thermally driven, of water in the upper portion of the earth's crust. These systems transfer heat from a rather deep igneous source to a depth shallow enough to be tapped by drill holes. Thermal energy is stored in the rock as well as in the steam and water which fill pores and fractures. Such liquid-dominated systems have been discovered much more frequently than the vapor-dominated type. Due to the effect of a higher pressure elevating the boiling temperature, hot liquid geothermal systems often contain water at temperatures exceeding surface boiling temperatures. In the major zones of convective upflow, it is possible to find coexisting steam and water extending to the surface and resulting in geysers and hot boiling springs. The Salton Sea field in California and the Yellowstone geyser basins in Wyoming are the major known hot-liquid geothermal fields in the United States.

### c. Geopressured Geothermal Systems

Geopressured regions consist of deep sedimentary basins filled with sand and clay or tertiary shale which are normally undercompacted below depths of 2 to 3 kilometers. As a result of this undercompaction, a portion of the overburden load is supported by the interstitial fluid pressure. These geopressured systems occur in areas where impermeable clay beds in a rapidly subsiding geosyncline insulate and trap the normal heat flow of the earth. The pressures at these depths exceed hydrostatic and often approach lithostatic. Waters in these zones are produced by compaction and dehydration of the marine sediments. Much of the trapped water contains little dissolved solids and this is very conducive to the solubility of hydrocarbon gases. This property combined with the high temperatures and pressures result in the natural cracking of the petroleum hydrocarbons. It is therefore common to find the reservoir fluids to contain 10 to 16 standard cubic feet of natural gas per barrel of fluid. Such dissolved gases would indeed be a valuable by-product of fluid production.

Geopressured deposits are found in continuous belts which are often bounded by regional faults and can extend for hundreds of miles. For example, the belt in the Northern Gulf of Mexico basin is 750 miles long, from the Rio Grande of Texas to the Mississippi Sound; it underlies the Coastal Plain inland for a distance of 60 to 100 miles; and underlies the Continental Shelf wherever drilled up to 150 miles offshore. Deposits are not continuous over the entire area, but rather are believed to exist in lenses, blocks, and partitioned volumes as a result of complex geological processes accompanying the rapid subsidence of the geosyncline. Other geopressured reservoirs discovered in the search for oil and gas include areas in the Gulf Coast, California, and Wyoming.

### d. Impermeable Dry Rock

Those geothermal regions where the heat is contained almost entirely in impermeable rock of low porosity offer the potential of a truly, immense energy source. Large plate interaction in the earth's surface along the North American west coast have resulted in volcanism, tectonic activity, and high heat flow which affect nearly all of the western United States. The large and at one time molten masses of granite which form the core of the Sierras and other masses termed batholiths were formed by this plate interaction generated heat. Recent activity of intrusive rock formation is clearly demonstrated by areas such as craters of the Moon in Idaho. In general, the western United States has an excellent potential for the discovery of large, hot, impermeable dry rock formations.

#### e. Magma Systems

These geothermal systems exist where the thermal energy is contained in liquid or near-liquid rock at temperatures ranging from 1100°F (600°C) to possibly 2700°F (1500°C). Magmatic activity in the Hawaiian Islands and in Alaska offer excellent potential for utilizing this type of system. Advancement in deep drilling technology may be required to reach magma resources in other locations in the United States.

### 3. UTILIZATION OF GEOTHERMAL ENERGY

The first commercial production of electricity generated from geothermal energy occurred in Italy, where dry steam was obtained from a well and passed through a turbine generator. Although the output was small, this represented a tremendous leap toward the development of a new energy source. Today, the geothermal power capacity in Italy is approximately 380 MW (ref. 35).

Other users include the USSR which is utilizing geothermal energy for the heating of domestic and industrial buildings, hot water supply, soil heating, heating of green houses, and balneological purposes. It is estimated that the coal equivalent of these energy uses was 15 million tons in 1970 and will approach 150 million tons by 1980. In Ireland, approximately 40 percent of the population live in dwellings heated by geothermal hot water and this figure may rise 60 to 70 percent by 1980. Irish geothermal hothouses produce in excess of a thousand tons of tomatoes, cucumbers, and lettuce each year. Geothermal uses in Japan consist of space heating and hothouses as well as animal husbandry which includes the breeding of alligators, eels, and poultry. New Zealand and Iceland also use geothermal energy for heating of facilities, with New Zealand even cooling facilities by means of lithium bromide absorption units. There are numerous other multi-purpose applications within each of the previously referenced countries and these include boron extraction, total energy, paper mills, and material drying (ref. 33).

There is approximately 500 megawatts of electrical generating capacity from geothermal resources in the United States today. In addition, there are many thousands of areas of likely geothermal sources which have been recently leased from the Department of Interior. Estimates of potential generating capacity that could be developed in the United States by the year 2000 range from 4,000 MW to almost 400,000 MW. Table 23 represents the most optimistic case (ref. 37).

Geothermal resources are now and are expected to remain economically competitive with conventional sources of water and energy. Although the energy costs for hot water dominated systems and other new systems are expected to be higher than the vapor dominated systems such as the Pacific Gas and Electric installation at the geysers in California, it is anticipated that such systems will remain economically attractive because of steadily rising conventional fuel prices (ref. 37).

#### 4. POTENTIAL OF GEOTHERMAL ENERGY FOR AIR FORCE INSTALLATIONS

The first area which will be discussed is an assessment from a military standpoint of the favorable features of geothermal resources. The ARPA funded Geothermal Working Group made the following comments in their report for the Air Force Office of Scientific Research (AFOSR) (ref. 36):

a. The relatively low cost, with estimates based on present production facilities for both capital costs and operating expense varying from about the same as to less than those of fossil-fueled and nuclear power plants.

b. The significant environmental benefit since much of the pollution associated with present power sources is avoided because no solid contaminants are emitted into the atmosphere and no radiation hazard is involved, and since the environmental consequences associated with geothermal energy sources appear to be more manageable.

c. The widespread occurrence of geothermal reservoirs.

d. The inherent, hardened nature of geothermal reservoirs in that they are underground and need have no external supply lines to the power production facility.

e. The multi-purpose use of the resource, that is, the reservoir can be tapped as a source of fresh water and of space heating and cooling, as well as for electrical power production, which is an advantage that geothermal resources have over all other energy sources, and that would be particularly significant at remote sites and in hardened facilities.

f. The suitability of geothermal reservoirs to be tapped for the generally much lower power requirements of military installations (1 to 2 megawatts and less for the smaller installations, such as remote radar sites, and about 40 megawatts for the larger installations such as Wright-Patterson Air Force Base,

compared to the 100 megawatts required for a typical city of 100,000 population) since the minimum production capability of a single well reservoir is estimated by the Geothermal Working Group to be less than 1 megawatt.

g. The adaptability of geothermal reservoir development and plant facilities to be enlarged or decreased by virtue of the flexible and modular character of their production and assembly (i.e., merely increase or decrease the flow from existing, or add or delete, wells and turbines) to satisfy varying loads due to base expansion or contraction, or for ease in relocation.

Unfortunately, these favorable features are not without question and criticism. As previously discussed in the Solar Thermal Conversion section, large scale use of any alternative energy source depends greatly on whether or not the Air Force will ever become a large producer of electricity; that is, will the Air Force ever produce most or all of the electrical power required at a majority of its large and fixed installations. At present, it is not envisioned that this will occur. The possibility of leasing geothermal reservoir rights to local utilities for their development and utilization and receiving reduced electricity rates may be another possibility to explore. The utilization of small geothermal wells for total energy systems or hot water sources for space conditioning presents yet another potential for the Air Force at remote sites or even normal bases. The flexibility of geothermal systems is not really any better than solar energy or wind energy systems since they are also modular in character. A question that is immediately raised concerns the use of geothermal resources for hardened facilities. Geothermal reservoirs, more frequently than not, occur in conjunction with young volcanism and mountain building activity as well as faults and fissures in the earth's crust. The location of hardened facilities in such areas is definitely questionable if discussing nuclear survivability. Obviously, each site would have to be analyzed individually, and the vulnerability of such systems to ground shock and motion would be addressed.

The second area to be discussed is the occurrence of geothermal reservoirs in reference to base locations. Of the four types of reservoirs, only two are considered to be available for possible extensive utilization. These two types are the liquid-dominated convective hydrothermal (hot water) and the geopressured (overpressured) resources. An ARPA funded study conducted under AFOSR grants has accomplished this task with results discussed in the following paragraphs (ref. 36).

Major known hot water reservoirs occur in the United States west of the Great Plains, including the states of Hawaii and Alaska. There are probably major reservoirs elsewhere in the United States since, for example, there are warm springs in Virginia, Arkansas, and Georgia, but their significance is not known. It has been estimated that, west of the Great Plains, as much as 75 percent of the area is underlain by hot water geothermal reservoirs of some significance and usefulness. For example, Mountain Home Air Force Base, Idaho; Elmendorf Air Force Base, Alaska; and Hickman and Wheeler Air Force Bases, Hawaii, are known to be located coincident with hot water reservoirs. The locations of hot water reservoirs in other parts of the world are not as well known, but major reservoirs are known to occur in Iceland (Keflavik AB) and in much of Korea, Japan, Taiwan, Philippines, Southeast Asia, many of the Pacific Islands, Panama Canal Zone, and near Ankara, Turkey. Military installations are located in all of these countries and areas.

Major overpressured reservoirs occur in the United States in the Los Angeles and Santa Barbara basins in California, in Wyoming, along the island chain and under the North Slope region of Alaska, and in a very large belt in the northern Gulf of Mexico basin about 750 miles along from the Rio Grande River in Texas to the Mississippi Sound and extending inland under the Coastal Plain at least 100 miles and offshore under the Continental Shelf at least 150 miles. Locations of Air Force bases coincident with these reservoirs include Eglin and Tyndall AFB's, Florida; Keesler AFB, Mississippi; England and Barksdale AFB's, Louisiana; and Ellington AFB, Texas. Locations of military installations coincident with overpressured areas in other parts of the world are not presently known, but it is known that overpressured areas have been encountered during oil and gas field drilling throughout the world. They are located in the Far East (Japan, New Guinea, Indonesia, Burma, India, and the South China Sea), in South America (Venezuela, Trinidad, Columbia, and Argentina), in the Middle East (Iraq, Iran, and Pakistan), in Africa (Algeria, Morocco, Nigeria, and Mozambique), in Austria, France, Germany, Holland, Italy, Hungary, Poland, Rumania, and in a number of areas of USSR.

## SECTION VII

## CONCLUSIONS AND RECOMMENDATIONS

## 1. CONCLUSIONS

There is indeed an energy crisis which is here today and will continue to be with us in the future. Even the most conservative of projected costs for conventional fuels is frightening, with fuel reserve estimates and consumption rates only adding to the severity of the problem. It is imperative that we all realize that the energy crisis will not just disappear nor will the problem be solved in the near future. The energy crisis will only vary in severity with "crunches" occurring now and then when demand increases or supply decreases more rapidly than expected of a particular resource. When this fundamental problem is understood, then perhaps we will realize that the most important question of energy policy is how should the nation and the world allocate its present resources for future generations. The development of new resources as presented in this report represents an investment for the future and by no means presents a solution for the problems of today. The quality of life, well-being, and security of the peoples of the world are dependent on the availability of large amounts of low-cost energy in useful form. The preparedness and capability of the Air Force and other services also depend on such energy as well as the ability to command this energy in such times and places as required by the mission at hand. This report does not address aircraft fuel which represents the direct arm of combat, but has investigated energy in relation to electrical power production and space conditioning for facilities. These facilities support the mission, and although the cost to operate and maintain these facilities may be small in comparison to the cost of aircraft and their operation, it is not small when considering the additional facilities and maintenance that could be purchased with only a portion of the \$300,000,000 it will cost the Air Force for facilities-related energy in FY 1975.

The first step in an energy program is to reduce consumption through implementation of conservation techniques and policies. The Air Force has had an active energy or utility conservation program, and in 1975 should show an estimated savings or reduction of 40,600,000 KWH or 15 percent when compared to 1973. Unfortunately, this energy consumption reduction is accompanied by a cost increase



of \$128,900,000 or 180 percent of the 1973 cost. It is readily apparent that energy conservation alone does not and cannot solve the problem.

The next step appears to be one of energy optimization which is basically similar to conservation, but entails actual modification of equipment or facilities to make them more energy efficient. Specifically, retrofication of existing facilities as well as the optimization of new facilities for better energy efficiency should be accomplished. Action has been initiated at a few installations, but in general, retrofication of existing facilities has not received much attention. Retrofitting techniques include better attic, wall, and floor insulation; duct insulation in unheated areas; storm windows and doors; and weather stripping. These techniques can be retrofitted into existing facilities with a considerable savings potential in life-cycle heating, ventilating, and air conditioning costs as well as reduced energy consumption. Operational administrative facilities, dormitories, and military family housing offer a tremendous opportunity for retrofitting and a detailed study followed by proof-of-concept-experiments should be accomplished as part of the Air Force Energy R & D Program.

During the same period that conservation and optimization techniques are being studied and employed, the Air Force must take an active part in developing alternative energy sources. It is not now nor has it ever been suggested that the Air Force take a lead role in new energy source development, but rather that it take an active part in the National Energy Program. An active part raises additional semantical questions, and will be clarified when the suggested program is outlined.

Prior to discussing the suggested program, an examination of possible applications should be made. As discussed in the main body of the report, a major question as to Air Force use of alternative energy sources depends on whether or not the Air Force will produce a significant percentage of the electrical energy required at both its large and small installations. Even after studying projected energy costs in the 1980 to 1990 time frame, it is envisioned that the high costs associated with purchasing necessary power production equipment, the training of qualified personnel, and the general operations and maintenance of such equipment will dictate that the Air Force not be a prime producer of electrical energy for its installations. It is very possible; however, that total energy or small power production systems will be utilized for certain areas or groups of buildings on a

base, and this should be considered when examining potential applications. Electrical power production will still be required at remote and/or isolated sites, and this represents the best opportunity for new power production systems.

Space conditioning offers excellent potential whether used in conjunction with a total energy system or separate heating and cooling system. Possible applications include individual facilities or clusters of facilities. Domestic hot water heating should also be included in this application.

Mobility applications are not considered as having potential since alternative energy systems are capital intensive, the systems are economically attractive only when in use and not in storage, and equipment specifications are too demanding. For example, Project 3782 (BARE BASE) equipment must be designed for climatic conditions of  $-25^{\circ}\text{F}$  to  $+125^{\circ}\text{F}$  ( $-32^{\circ}\text{C}$  to  $52^{\circ}\text{C}$ ) with a minimum life of 5 years when deployed twice a year or a minimum storage life of 10 years.

## 2. RECOMMENDATIONS

It is recommended that the Air Force consider the following actions for a viable Alternative Energy Source Research and Development Program:

a. The Air Force must ensure that personnel maintain awareness of the state-of-the-art of new energy source utilization and that cognizance of national programs and policy is maintained. It is imperative that staff personnel inform R&D Project Officers of DOD and USAF policies concerning energy system development and utilization.

b. A study of retrofitting Air Force facilities with emphasis on Military Family Housing (MFH) units should be undertaken. The first year effort should consist of the study and metering of MFH units at representative installations (based on heating and cooling degree data), followed in the second year by retrofitting and proof of concept experiments.

c. The Air Force should take part in the Solar Energy Heating and Cooling Demonstration Act and work with DOD to place demonstration units at the sites recommended in section IV of this report. Technical advisors or project officers working in energy should be consulted concerning those installations selected as well as the type of system proposed. Coordination between R&D and Civil Engineering staffs are essential, e.g., AFWL and AFCEC project officers were never informed of USAF/DOD sites selected for initial DOD participation in the Demonstration Act. If there is technical expertise in the Air Force in these new energy areas, it should be identified and properly used.

d. USAF/DOD should take an active part in developing wind energy conversion systems to include making electrical requirements, wind data, and other relevant information known to ERDA and NASA for possible Proof of Concept Experiments (POCE) and in-user environment testing. Certain Alaskan sites as well as major CONUS installations offer excellent wind power potential, as shown in section V of this report.

e. The AF should address the prospect of making an assessment of solar energy heating and/or cooling feasibility a mandatory item to be included in Military Construction Program packages commencing with the 1980 program. This action obviously presents certain problems concerning base level engineer familiarity as well as the Corps of Engineer experience with solar energy, but the possibility must be investigated. Facilities such as schools, administrative or headquarters buildings, operational (SQ OPS) facilities, and MFH represent prime candidates. Domestic hot water and swimming pool heating must also be considered.

f. Planning should be initiated for future educational programs at the Air Force Civil Engineering School and at the Sheppard AFB Technical Schools dealing with basic solar thermal processes, and the design, construction, operation, and maintenance of solar and wind energy systems. Perhaps for this reason, solar energy demonstration projects should be considered at these two installations.

g. Additional study of geothermal applications is necessary, and USAF installations for test systems should be identified and the information forwarded to ERDA. Unfortunately AFWL does not have the capability to perform an adequate study of this resource, and for that reason section VI presents only a cursory look at the potential.

h. The feasibility of jointly funding ERDA Proof-of-Concept-Experiments for alternative energy sources should be investigated. The USAF could provide facilities and certain portion of funding as well as operation and maintenance of equipment with ERDA supplying the remainder of required funds. Both parties would benefit with USAF gaining valuable experience in O&M of alternative energy systems.

i. Although the USAF Energy (Facilities-Related) R&D Program has not received much support, serious consideration must be given to maintaining an effort which would provide technical advice to the field; maintain cognizance of the national program and the state-of-the-art of advanced energy sources;

and monitor Air Force participation in the Solar Heating and Cooling Demonstration Act as well as other Proof of Concept Experiments for other solar energy or wind energy conversion systems. The required funding for such a capability would be less than 0.2 percent of the cost of facilities-related energy in 1975, yet such a program would not only reduce AF energy costs through energy conservation and utilization of new energy sources, but would help conserve our precious and finite fossil fuels.

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